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FINAL REPORT FOR PROJECT ULTRA ECHO

CONTRACT NO. NAS5-3964

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For

GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland

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SUMMARY

Many improvements on the balloon satellites of the Echo class can be realized by the development of inflatable modules, 1 inch by 6 feet long, of ultra-thin polyethylene film which serves as carrier for a 1/8 x 1/8 inch metal mesh of 1- or 2-mil wires, rigidly joined at all intersections. These tubular modules serve as the structural members of a space truss which can be of any configuration, and is erected in space after orbit is achieved, by inflating the modules so that each becomes a pressure-stiffened cylinder. Inflation strains the metal mesh into its plastic region, and the permanent set in the metal is retained indefinitely after the pressurizing gas is lost. The film is melted by exposure to the sun and withdraws onto the metal; thereafter the extended truss presents a large surface as a conductor to reflect electromagnetic waves, but a small surface to drag and radiation forces which degrade the orbit.

Studies of the joining problem settled on resistance welding as the only acceptable method, and materials studies settled on 347 stainless steel. 1 x 6 inch modules were hand made, and the welding process was mechanized, step wise, culminating in an automatic winding and welding machine which will make 8 feet of tube (more than 1500 individual welds) in an hour.

A space truss 22 feet in diameter was assembled from the production of the machine and made available for test as an electrical reflector.

INTRODUCTION

The Genesis of Project Ultra-Echo

The Echo satellites were early demonstrations of the feasibility of inflatable structures in orbit as passive communications satellites:

Echo I--a 100-ft. sphere of aluminized plastic was launched August 12, 1960 and is still visibly in orbit being believed to retain its spherical shape although it is acknowledged by its designer and fabricators that the balloon has lost its charge of inflating gas.

Echo II.--a 135-ft. sphere of Mylar with aluminum foil bonded inside and out was launched January 25, 1964; the inflated balloon weighed 535 lbs., and became the subject of the first joing US-USSR space experiments. Its radar cross-section did not change much in the first year in orbit. There is, of course, perturbation of the orbit of both these balloons by dissipative forces which work over the large surface of the skin. *

Sea-Space Systems competes with the makers of Echo I and Echo II and on May 9, 1963 submitted to NASA Headquarters an unsolicited proposal for an inflatable spherical radar reflector which would differ fundamentally from Echo II of which the launch was anticipated in nine months. In essence, the SSS studies were directed toward a sphere to weigh the same as Echo II but to attain a diameter of 405 ft. thus realizing a 9-fold increase in radar scattering cross-section over Echo II, and hopefully, in consideration of other factors, a 10-decibel increase in the reflected power.

Some of these other factors were (1) a large increase in the rigidity of the sphere after it has lost its inflating gas, owing to its configuration as a space truss with structurally redundant members, (2) the related minimization of the departures from sphericity of the reflector, which sphericity would not depend on retention of the inflating gas, (3) reduction of drag and pressure forces on the satellite leading to enhancement of the orbital lifetime.

The SSS proposal was passed by NASA Headquarters to GSFC and on December 5, 1963 SSS supplemented that proposal by adding a metallic

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* Further data is readily available in, for example, Astronautics and Aeronautics, 1963, 1964, and 1965, Scientific and Technical Division, NASA, Washington, D. C.

meshwork over the whole surface of the 405-ft. sphere. On May 29, 1964, SSS further supplemented the subject of proposed investigation by enlarging the target sphere to 425 ft., and on June 19, 1964, a work statement was achieved and Contract No. NAS 5-3964 went in force. The effort was "kicked off" in technical discussions at Sea-Space during the visit there on July 17, 1964 by GSFC representatives.

REQUIREMENTS-OBJECTIVES AND PURPOSES

The objectives and purposes of the Sea-Space proposal of May 9, 1963 are permanently registered in a patent for a "Passive Communications Satellite" (application September 25, 1963, issued October 4, 1966: 3,277,479) which begins by listing eight disadvantages of satellites of the Echo class:

1. Relatively large weight,
2. Inflation difficulties,
3. Short effective life,
4. Poor electromagnetic properties if partially deflated,
5. Orbit perturbations due to solar winds and aerodynamic drag,
6. Film memory problems,
7. Susceptibility to damage by micrometeorites and meteorites, and
8. Danger from over-pressures in the event a large megaton blast was produced in space, even though the blast is thousands of miles away.

The Sea-Space goal was to begin by making a tubular module, 1 inch in diameter and a few feet long. The tube would be a super-thin polyethylene film serving as carrier of a braided or woven metal meshwork of which all intermetallic contacts had been cold welded or otherwise rigidly joined. Inflation of the tube would stress the metal into its plastic region while requiring the film to become a pressure-stiffened cylinder. Pre-assembly of the uninflated modules would be such as to give, on inflation, a three-dimensional space truss in which all metal elements had received a permanent plastic strain. Rigidity of the space truss no longer requires the stiffening by internal pressure, and the pressure-containing polyethylene film melts and withdraws onto the metal mesh, as a matter of surface forces under the thermal conditions of the orbital environment. A preferred operational technique with the system involves launching and inflating the satellite on the dark side of the earth, the aluminum being elongated beyond its yield strength upon reaching a certain altitude. When the satellite reaches sunlight, the aluminum would already have received its permanent set and the super-thin polyethylene film would be allowed to melt. This results in a plastic film around the aluminum grid members. The net result is that the aluminum network would be the only principal surface area to receive solar radiation pressure or be affected by aerodynamic drag.

There are very many advantages of achieving the open metallic network in orbit and these may be listed for comparison with the closed surface of reflectors of the Echo class:

1. A weight advantage: a 405-foot diameter open network sphere can weigh less than a 135-foot diameter solid satellite.

2. A gas advantage: the inflation gas required is approximately four orders of magnitude less than that for a solid sphere, which would mean fewer inflating problems as well as higher pressure capability.

3. A reliability advantage: once all the braided aluminum modules are stressed past yield, no further pressure requirements exist for the life of the satellite.

4. A radiation pressure advantage: solar radiation pressure, earth radiation pressure, and earth reflected solar radiation pressure should not affect the open mesh satellite in comparison to a passive satellite having a closed-skin surface.

5. Aerodynamic drag advantage: the open network design and small effective surface area would decrease aerodynamic drag problems markedly.

6. An ephemeris advantage: the decreased forces on the satellite will have a smaller influence on the orbit and thus insure improved tracking capability.

7. An electromagnetic reflectivity advantage: the increased size of a 405-foot sphere enables a theoretical 10 db gain over a 135-foot satellite with a closed skin.

8. An environmental advantage: thermal effects in orbit result in the plastic carrier melting and withdrawing to the metal mesh under surface tension forces, resulting in an open metallic weave with no pressurization requirements, ultraviolet sensitivity and film memory problems; only the permanently set metal will be required to maintain the shape of the reflector.

9. A hazards of space advantage: a space truss would have orders of magnitude less probability of damage from micrometeors, meteroids and/or pressure pulses from nuclear tests in space.

10. A long life advantage: because of the above advantages, a space truss satellite would be expected to have much longer effective life than an inflated satellite with a permanently closed skin.

11. Reliability: redundance of the design of the space truss is expected to allow module failures without satellite failure and positive retention of design shape through a "stabilized shell" which is statically over-determined.

12. The option of isotropic or non-isotropic design. For example, the modular method can as easily be adopted for the design and construction of a "corner reflector" in orbit as for a sphere. All the possibilities of better-than-spherical scattering thus come open.

DEVELOPMENT APPROACH

Against the background of the passive communications satellite systems requirements, there is a definite sequence of steps toward realizing the advantages listed above. These may be outlined as follows:

1. Development of the 1-inch x 6 ft. modules

   (a) A method of mechanically joining metal wire or tape, in the range of 1 mil thick, such that

      (1) the overall mechanical properties of the parent wire are not degraded,

      (2) the joints are reproducible,

      (3) the electrical conductivity across the joints is good,

      (4) one joint is no more than 1/8 in. from its nearest neighbor.

   (b) Mechanization of the method towards

      (1) reduction of unit cost per module,

      (2) uniformity of quality control,

      (3) mating of the metal meshwork with the polyethylene film which will serve as its carrier.

2. Development of a metal net to serve as reflector with

   (a) 1/8-inch interstices,

   (b) thousands of square feet of surface,

   (c) the capability of being deformed to a definite curvature.

3. Construction of a segment of a sphere for the extension of about 400 ft.^{2} of the surface net as an electromagnetic reflector.

   (a) questions of the base of the extensible structure,

   (b) testing mechanical performance in inflation of the space truss,

(c) testing electromagnetic performance of the skin meshwork.

4. Analytical studies of the orbital insertion and residence.

    (a) packaging modes for launch, inflation modes at insertion,

    (b) melting and withdrawal behavior of the polyethylene carrier onto the metal meshwork,

    (c) temperature excursions in the permanently deformed metal, in their dependence on the orbit.

    (d) the associated mechanical flexures of the space truss which serves as substructure for the reflecting mesh and the departures from sphericity of this mesh.

TECHNICAL EFFORT

Welding Considerations

Cold Pressure Welding. Initially, the contractor's major welding effort was directed toward cold-pressure welding of aluminum and stainless steel. Several different alloys of aluminum and stainless steel were tested to determine the possibilities of cold-pressure welding. It was determined that in the sizes that are applicable to the satellite weight desired, cold-pressure welding could not be realized. The control of the pressure weld is such that in the very small wire gauges, either the wire intersection does not weld or the intersection becomes so weak due to cutting action that the strength of the grid is in question. The utilization of flat ribbon aluminum 1 x 5 mils did not materially improve the welds.

Consideration of the system weight budget indicated that an aluminum wire of 1-1/2 mil diameter would have to be used. After handling 2 and 3 mil aluminum wires, it became evident that utilization of aluminum was questionable at this size. Since cold-pressure welding results would become worse if the 1-1/2 mil diameter were used, it appeared that cold-pressure welding was unsuitable.. As a consequence, the contractor initiated investigations of other techniques for providing welded joints so that a matrix with good structural and electrical properties would result.

Other Welding Methods. On the cold-pressure welds being found unsatisfactory, the contractor initiated investigation of the following welding techniques:

(1) Ultrasonic welding
(2) Conventional resistance welding
(3) Capacitive discharge welding
(4) Laser welding

In general, upon initial contacts, most equipment manufacturers indicated that welding could be accomplished on the alluminum wire; however, test results never indicated that more than 10 to 20% of the welds were satisfactory. The contractor undertook to build a small capacitive discharge welder directly suited to the job of welding small wires. The results obtained with this "in house" welder were again scattered and it was thought would not produce any better reliability.

The special manufacturing problems associated with either ultrasonic or laser welding equipment did not justify these techniques as primary possible solutions. In the event that resistance or capacitive approaches did not prove satisfactory then the ultrasonic or laser approaches would have been reconsidered, but would very doubtfully have led to production equipment.

A summary of the more important contacts is given below:

L. C. Miller Welding Co.	Equipment was too large.
Airite Products	Equipment could weld steel but not aluminum.
Hughes Aircraft Co., Vacuum Tube Prod. Div.	Stated their welding machines would weld our material but they were unable to weld the samples we sent them.
Unitek Corp.	Were able to make some welds successfully but could not be consistent.
Associated Spot Welders	Said they could weld the wire, but were not able to weld the samples.
Korad Corporation	Builds laser units for Linde Co. and they said they could weld the wire, but it would have to be done through Linde.
Linde Company	Only had one demonstration machine. It was not acceptable.
Hughes Aircraft Co., Newport Beach, Calif.	Samples were sent to their Laser Division but have heard nothing as of this report.
Sonobond Corp.	Manufactures ultrasonic welding equipment; no answer to our inquiry was received.
AMF Thermatool, Inc.	Were contacted with regard to their ultrasonic equipment; said they would contact us. No results yet.
Weltek	Manufacture miniature precision welders and says they can weld the aluminum wire. No results to date.

Choice of a Power Supply. In considering the welder to produce the electronic test specimen, it became evident that choice of a power supply would necessarily dictate elements of the design as well as the quality of the welds. As a consequence, considerable investigative effort was expended in determining the proper power supply and how it could be made available for the purposes of the contract without purchase. These investigations are summarized below.

> Welding power supplies from Hughes, Thermatool, Miller, Linde, Sippican, and Weltek were investigated. SSS welding experiments were run with a Weldmatic power supply Model 1049B, a Tweezer-Weld 18 Watt Second Condenser Discharge, and a Tweezer-Weld DC-80 power supply plus the unit finally selected. The only unit that fulfilled the requirements as to speed of discharge and the low current requirements was the Weltek Model AC-5. This unit was rented and used.

In House Welding. In anticipation of the problems in building a large scale welding machine, an extensive in house, small wire welding investigation was conducted. The in house tests resulted in an understanding of the parameters that affect a weld and provided the basis for rejection of unsuitable metals. Most of the effort was devoted to resistance welding techniques after the alternatives to this conventional technique had been proven impractical.

Resistance welders use the resistance of the contact point of two wires to melt the wires locally until they fuse, making the weld. Any variation in resistance or current input will affect the heating of the wires and thus, the quality of the weld. It can be seen that voltage, discharge time (and pulse shape), electrode pressure, wire diameter, ambient temperature, and oxide coatings on wire and electrodes are all factors involved in obtaining the desired molten state in the wire.

The first in house welder consisted of a single aluminum electrode that was hand oriented to contact two crossed wires supported by a conductive surface. Any discharge through the electrode to the conductive surface goes through the crossed wires. This technique was understandably slow but it was instrumental in determining the factors that need to be optimized for a good weld. It was discovered that the aluminum electrodes deteriorated after multiple welds and they were soon replaced with copper-chromium alloy components. This equipment is seen in Figs. 25 and 26.

The 13-Electrode Welder. With an established welding capability, the objective was to see if the welds produced met the requirements of the project. For this purpose, a second welding apparatus was constructed that was an extension of the first welder. Grid samples of a 1/8-inch mesh that were 1-1/2" x 1-1/2" were produced by this welder. The head contained thirteen electrodes, each individually spring loaded and arranged in two rows. (See Figure 24.) The electrode spacing is such that they will contact thirteen wire crossings, thus with the weld head lowered thirteen welds can be made by switching electrodes, one at a time to the welder power supply. The spring loaded electrodes assure the ability to follow the rapid expansion and contraction of the weld nugget and giving the proper amount of follow-through pressure for the production of sound, porosity-free welds. The electrodes are made from 1/8 in. round stock and tapered to 1/16 in. at the contact point. The tip diameter dimension allows sufficient tolerance in case of misalignment to assure contact with the weldment. The low conductivity of the material to be welded, annealed stainless steel, dictated the selection of a high conductivity electrode material. RW MA Class 2, copper-chromium alloy of 83 B Rockwell hardness satisfies the requirement.

Materials Selection

The contractor expended his initial efforts in attempting to prove, with experimental hardware, mesh characteristics so that positive data was available on which to base the tube design and satellite covering mesh. In this regard, the contractor executed the following investigations which are primarily associated with the physical handling and welding of small diameter wire that appear suitable for application to the proposed structural tube and mesh technique.

Many materials were considered by the contractor to form the electrically conducting structure of the proposed satellite. The material must primarily satisfy the necessary electrical properties and it also must be submissible to a difficult fabrication process.

Aluminum. In regard to the use of aluminum wire for the proposed structural technique, the following appear pertinent:

1. The handling and strength problems associated with 1-1/2 mil aluminum wire make this gage extremely questionable; this is particularly true for the type of production process envisioned.

2. The contractor experienced inability to achieve over 10 to 20% weld reliability with any welding technique for the wire size in question.

3. It is dead soft aluminum which can be drawn to such fine wires and such unalloyed aluminum does not subsequently work harden to a sufficiently high value of the elastic stress.

Thus, it was concluded that no further efforts would be expended trying to handle untreated aluminum.

Gold Plating. Both aluminum foil and aluminum wire samples were gold-plated in an effort to improve the weldability. Unfortunately, the resulting samples were very brittle and, due to very promising results with stainless steel, it did not appear worth while to proceed with an annealing cycle and/or welding samples.

Sprayed Aluminum. In an effort to continue to utilize aluminum, the possibility of spraying or plating aluminum on a plastic fiber grid was investigated; and the possibility of dip brazing an aluminum wire grid was tried. Each of the techniques was expected to lead to excessive weight at the first but it was felt that if enough promise was shown, possibly sufficient effort could be directed toward a specific technique to reduce the elevated weights. A number of sprayed samples were generated; several samples of plating with copper were also effected. Generally speaking, both the plate and the spraying techniques showed promise; however, the weights at this time are a factor of 10 away from realization of an attractive answer. Further, it is not known whether either of these approaches would satisfy the tube structural problem.

The dip brazing sample was entirely unsatisfactory since quality control seemed difficult to achieve and the technique did not appear at all practical in regard to the wires employed. The sample exhibited brazing weights well in excess of that attributable to the wire itself.

It is not felt that any of these processes should be pursued further, particularly in view of the fact that several of the basic considerations may not be answerable in a practical manner.

Stainless Steel. The most impressive characteristics were displayed by some of the stainless steel alloys. Primary attraction to stainless steel came from its relatively good weldability. Initial work was done with 302 stainless steel and annealed 304 stainless steel. It was found that the low carbon 347 stainless steel was a more ductile and weldable alloy and also exhibited good strain hardening (see Figures 27 and 28). Although, in consideration of weight, stainless steel is not the best material for a structure in which flexural stiffness is sought, this consideration was off-set by the successful welding of thinner wires (see the following Table I of comparative satellite weights).

Weight Reduction Investigations. The contractor expended investigative efforts toward reducing the weight of the satellite structural tubes/ electronic response mesh. These efforts fall into the following categories and are discussed below:

Reduced Wire Size. The contractor obtained some .0007 in. diameter stainless steel wire and attempted to make a 1-1/2 in. x 1-1/2 in. grid. The uniformity of the welds in this hand operation was, in general, poor. It is estimated that not over 30% were good welds. However, it is pertinent to note that this extremely small diameter wire could in principle be welded using the SSS developed techniques and it is anticipated that should such a small wire size eventually be used that an acceptable level of quality control could be achieved with automatic mesh welding.

Metal Etching. Acid etching of 2 mil wire samples was effected to test this method with mixed results. The attempts to etch 302, 304 and 347 stainless steel wire tube meshes to reduce their weight resulted in dissolution of the 302 stainless steel mesh, and severe pitting in the 304 and 347. The minimum diameter

Table I

GRID REFLECTOR WEIGHTS
FOR A
425 FT DIAMETER SPHERE

Material	Size	Spacing	Weight
Aluminum	3 Mil Dia.	1/8 Inch	940 Lbs
Aluminum	2 Mil Dia.	"	417 "
Aluminum	1-1/2 Mil Dia.	"	236 "
Aluminum	1x5 Mil Ribbon	"	662 "
Stainless Steel	1 Mil	"	215 "
Titanium	1 Mil	"	175 "
Platinum/Tungsten	1 Mil	"	573 "

achieved from an original .002 in. was .0015 in. Etching below this diameter resulted in spontaneous failures. Meaningful U.T.S. tests became impossible in the presence of pitting. Inquiries indicated that an electropolish process would give results superior to the acid etch process, but the procedure is slow and involves multiple components, so that it is not clear how it could ever be adapted into the production of hundreds of feet of tube and of square feet of mesh, as the goals of the project require.

Annealing Stainless Steel. Although stainless steel was comparatively easy to weld, the wire strengths were somewhat unreliable due to softening and pinching around the welds. It was found that by annealing the welded wires in an inert atmosphere, the weld reliability could be increased significantly and the region available for work hardening under stress greatly enlarged. Several combinations of welding and annealing were tried to arrive at the most reliable samples; anneal-weld-anneal, weld-anneal, anneal-weld (see Figures 27 and 28). The weld-anneal procedure produced the best results.

Testing Welded Samples. The question of weld reliability was one of great importance to the success of the project and a considerable effort was made in testing the welded wires. The tests were mainly concerned with single wire strength, electrical continuity, and elongation characteristics. The standard test consisted of loading a wire (having 5 orthogonal welds) to failure and taking load-elongation measurements. Initial tests showed that the stress-strain curves were the same as the unwelded wire through the elastic region but failure took place a short distance into the plastic region and invariably at a weld. Adjustment of electrode pressure helped this situation somewhat but the real problem was due to necking and softness at the weld. The welding process was annealing the intersections. Tests in annealing the whole assembly showed that this preferential breaking at the weld would be substantially relieved by annealing the welded wires at 1900^{o} for 1/2 hour in a hydrogen atmosphere. Subsequent tests of the welded annealed wire indicated that it had properties very similar to unwelded wire and failure was seldom at a weld (refer again to Fig. 27 & 28). The wire testing equipment used to determine suitable materials for the project was later used to determine the effectiveness of subsequently developed welders and to insure weld quality.

Consideration of Other Metals. Investigations into the use of other metals yielded local supplies of titanium and platinum/tungsten wires with diameters that were small enough to be applicable to the project. Very little success was met in trying to weld these metals with the available equipment. The following chart shows that both these samples were also far inferior to stainless steel in the stress-strain characteristics, see Table II.

Table II

Material	Condition	Size	Strength	Elongation
304SS	Annealed	.0021" dia.	8 oz.	25%
302SS	Hard	.002" dia.	19 oz.	~0
Aluminum	Hard	.002" dia.	8 oz.,	2.5%
Aluminum	Annealed	.002" x .005"	5 oz.	2.5%
Aluminum	Annealed	.0015 x .015"	1-1/2 oz.	.8%
Platinum/Tungsten	Stress Rel.	.002" dia.	12-3/4 oz.	small
Titanium	Annealed	.0025" dia.	7 oz.	small
Titanium	Annealed	.001" dia.	1.5 oz.	small

Other Grid Investigations. Tests to reduce the weight of the electronic mesh by replacement of the welded wire with a very fine coated fiber mesh were conducted. It was felt that utilization of fine plastic fibers vapor-deposited with aluminum or cadmium would provide an excellent covering for the welded tube structural matrix. The results were not encouraging for the following reasons:

1. Point to point electrical resistances were more than could be tolerated.

2. The resulting coated mesh was several orders of magnitude too heavy.

3. Folding of the coated mesh resulted in discontinuities in the conductive surface.

4. The coated meshes did not satisfy the tube structural problem.

Due to the more promising properties of stainless steel, it was concluded that these lines of investigation should be terminated.

Metallic coated glass fibers were also tested. SSS test results are included on the table below. Although the coated glass fibers were electronically acceptable, they presented a difficult fabrication problem and were thus discounted when compared to other materials.

TABLE III

COATED GLASS FIBER DATA SUMMARY

Single thread, maximum ultimate strength	1.66 gms
Diameter as coated	0.0005 in.
Flexure	180° bend on 1/64 in. radius
Electrical resistivity	0.91 ohms/ 1/8 in.
Lineal weight	2.94×10^{-4} gms/ft.

Integration of Plastic and Wire

Wire--Plastic Module Construction. The basic structural module consists of a bladder tube within a wire mesh grid tube. The pressurization and resulting extension of the plastic bladder, also extends and strain hardens the grid tube. Thus, by a temperature rise and resultant expansion of a sublimating powder, the module is pressure stiffened and its metal mesh is permanently set so that the satellite is deployed and rigidized. Of primary concern was the physical compatibility of the plastic bladder and wire mesh tubes. Initial tests with short modules indicated that the end closure technique would have to be handled carefully to avoid end opening in a peeling manner. (See Figures 29 and 30.) A satisfactory result was achieved by the use of a multiple module connector developed by SSS. It is illustrated in Figures 30 and 33.

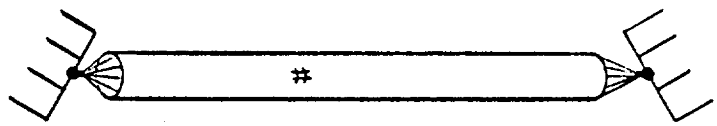
Polyethylene Withdrawal Under Heating. It would be highly desirable to produce a satellite with low cross-sectional area to reduce excursions due to solar radiation pressure. In this regard, the contractor conducted many tests concerned with the withdrawal onto its armature of an inflated plastic bladder under the surface forces which are effective at elevated temperatures. In general, it can be said that the plastic area can be reduced to approximately 1/10th of its inflated area within a 15 min. period. It is anticipated, however, that with extensive time periods at elevated temperature, both width and length will experience contraction characteristics.

It was thought that module deformations could result from distortion of the plastic tube. Tests that were made indicated that resulting stresses could be limited to either circumferential or longitudinal, depending on the direction of film orientation in the plastic tube. Either of these stress conditions proved to be acceptable in the performance of the module.

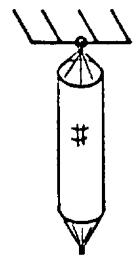
The following two tables are a summary of these investigations. It was concluded that by judiciously choosing film orientation in tube construction, and by maximizing film memory characteristics, the deformations of the module are inconsequential, and that enough of the plastic film would withdraw itself onto the mesh to make the effective cross-section of the satellite for radiation pressure that of the metal mesh alone. The area presented to the sun is thus finally that of a screen rather than that of a sail.

TESTING METHODS FOR P.E. HEAT CONTRACTION

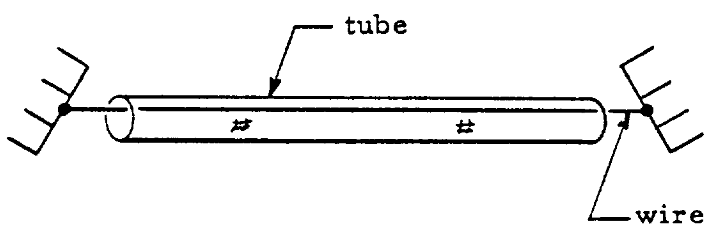
METHOD #1 Suspension of Tube by both ends



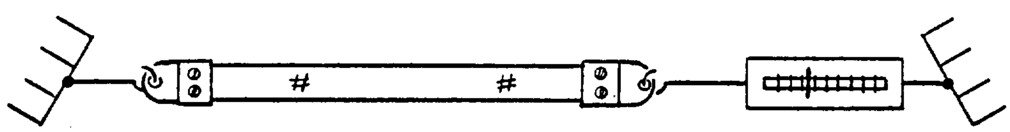
METHOD #2 Single end suspension



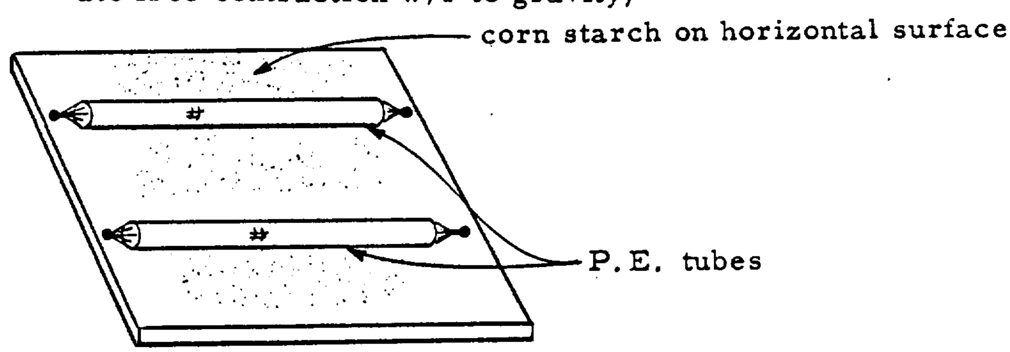
METHOD #3 Supported by a wire



METHOD # 4 Apparatus to measure hot & cold tensions



METHOD #5 Horizonal Surface covered with corn starch (to facilitate free contraction w/r to gravity)



CONTRACTION CHARACTERISTICS OF THIN POLYETHYLENE TUBES

Test Run	Material Direction	Polyethylene Gauge	Test Temperatures	Test Method	Length-Inches Orig. /Final	Final Length -% of Orig.	Layflat Width-Inches Orig./Final	Final Width -% of Orig.	COMMENTS
1	T	1/2 mil	200°F	1	30/grounded	N. A.	1. 41	-	Tube sagged and grounded to bottom of oven. Diameter constricted (machine direction).
2	T	1/2 mil	200°F	2	31/grounded	N. A.	1. 41/. 22	16%	Tube elongated under its own weight and grounded. Diameter constricted (machine direction).
3	T	1/2 mil	200°F	3	30/30	100%	1. 41/. 31	22%	Tube adhered to wire. Diameter constricted (machine direction).
4	M	1/2 mil	200°F	2	37/14	38%	1. 41	-	Continued heating resulted in failure
5	M	1/2 mil	200°F	2	30/9. 5	32%	1. 41/. 5	35%	5. 5 lbs tension began return to original length.
6	M	1. 2 mil	200°F	4	24	-	1. 41	-	Max. hot tention - 4 oz Max. cold tension - 8 oz Failure resulted when heating continued.
7	M	1/7 mil	200°F	2	10/2. 5	25%	1. 25/. 5	40%	Width did not change except by fusion of adjacent surfaces.
8	T	1/7 mil	200°F	2	10/20 before failure	-	1. 25	-	Constriction of diameter was evident (machine direction). Elongated under its own weight to failure.
9	M	1/7 Mil	250°F	5	10/2	20%	1. 25/. 56	45%	3 hrs oven time
10	T	1/7 mil	250°F	5	10/10	100%	1. 25/. 12	10%	3 hrs oven time

Note 1. In all cases, specimens were partially inflated during testing.
Note 2. Oven times are 15 minutes unless otherwise specified.

The 22-ft. Segment for Electrical Test. It was a task to fabricate and an end item to deliver a circular segment, 22 ft. in diameter, of a sphere which would be on a radius of curvature of about 200 ft. This segment was to be made of inflatable space tube according to the spirit of the present effort, and was to be covered with reflective mesh and then tested at the appropriate radio engineering facility for its performance as a reflector. But the difficulty immediately arose that the very light structure implied in all the present effort is not strong enough against the body forces applied to it by a 1-gravity force field. In other words, an ultra lightweight structure which is of interest for its service in orbit is very difficult to test for electrical performance at sea level. Accordingly, GSFC had fabricated by another contractor a torus having a principal diameter of 21 feet and a lesser diameter of 1 foot. This large ring was to be inflatable, and as it is seen in elevation in Fig. 31, its outer diameter would realize, upon inflation, the 22-foot circular diameter required for the test. Stretching across the bottom of this torus was a circular membrane, and the SSS space tube together with its reflective mesh was to be stretched across the top of the same torus. This configuration was to yield a discus-shaped structure, more or less hermetically impermeable which would on inflation distend itself upward to reach the spherical radius of curvature of about 200 feet as required for the test. Inside the segment, a disposition of space tubes would, on inflation, construct within the segment the space truss which is the objective of all the present effort. This space truss is seen in plan in Fig. 32, while the detail of the SSS union among as many as six members of the truss is seen in Fig. 30 and illustrated in Fig. 33. At the left of Fig. 33 are shown a couple of styrofoam shapes on which SSS tried its bonnet with a drawstring on the underside, as a matter of demonstrating the feasibility of the method.

In the actuality of the test exercise, directed towards investigating the reflectivity of the spherical mesh, the GSFC torus was to be bolted (plastic bolts were to be used) to a still stronger sub-structure which could be tilted through a small zenith angle so that the pointing characteristics of the antenna could be studied. Clearly, this enormous structure could not be shipped after inflation and SSS fabricated it in house, folded and packed it, and shipped it to GSFC. The method of assembly depends on taping the bonnet at regular intervals along the circumferential run of the torus, but not until after the space tube interior structure has been assembled according to the plan seen in Fig. 32.

Data Analysis

The tests described above generated the data contained in Figures 27 and 28 and Tables I, II, and III. The choice of welded and annealed 347 stainless steel as the optimal material is clearly demonstrated by these presentations. It is required of the space tube elements that they be strain hardened by a plastic liner. This function is most easily facilitated by a material that has a low yield point and a long region of plastic deformation. A low yield point will permit lower bladder pressures and less chance for failure of the liner system.

In addition to the demonstrated welding capabilities, it can be seen from these tables and graphs that a stainless steel alloy is superior in elongation to the other materials tested.

The graph of Fig. 27 compares two welded stainless steels (annealed and unannealed) that had initial promising characteristics. It can be seen that the weld first, anneal second procedure produced the most desirable characteristics. Although 347 stainless steel had a higher yield point than 302 stainless steel, its desirable welding properties and greater range of plastic elongation make it functionally superior. The necessity of the annealing step is also clearly shown.

The graph of Fig. 28 demonstrates variations in the weld-anneal sequence for 347 stainless steel. Again, the weld first, anneal second procedure seems to be the most profitable.

Thus, it was concluded from the electrical properties, weldability, and structural-mechanical properties that 347 stainless steel wire was superior to the other materials tested.

The Winder-Welder

Laying the Basis for a Design.

Experimental Tube Welder. Following the completion of enough welded wire samples to demonstrate the ability to weld thin wires and provide specimens for satisfying tests, the welding investigations were directed toward design and construction of an automatic welder that could mass produce meshworks in the form of long tubes.

Prior to construction of the prototype winder-welder, an experimental jig was constructed. The experimental jig for welding tubes consists of a single electrode head and a single base electrode. The base electrode is a 12 in. long x 1 in. diameter round bar of RWMA Class 2 copper chromium alloy. The bar is supported at the ends by journals with indices which keep it in position under the electrode head. Welds are made sequentially by moving the mandrel with final positioning effected by microscope. The base electrode is then moved to a new position by rotation and longitudinal sliding as necessary. Upon completion of welding the end journals are removed from the bar electrode and the finished wire tube is slipped off over one end. The photos that follow show the basic hand-operated mandrel and utilization of a microscope to position the electrode, and the resulting tubular wire grid. This experimental welder led to the design and fabrication of a prototype winder-welder.

Results of the experimental tube welder were generally much improved over that accomplished previously. However, several rather important facts came to light in regard to the requirements for the prototype welder design; these include the following:

a. A long line of welds brings about dimensional changes large enough that wire tension and relative movement characteristics must be accommodated.

b. During performance of the weld, no tension must exist on the wire or else the "working" phenomena is exaggerated and the weld may part.

c. Uniformity of the welds is achieved through the utilization of a microscope in order to provide accurate alignment.

d. No matter how carefully the initial wire matrix is wound, subsequent handling and welding operations disturb the matrix to the extent that uniformity from weld to weld is lost. Thus the members to be welded must be held by auxiliary means, and/or the winding done just ahead of the electrode passes.

A Prototype Machine: Do's and Don't's. The winder-welder utilized a conventional lathe especially long-bedded, with the winding and welding auxiliary devices mounted thereon. There were several basic considerations to be met in producing the prototype winder-welder. The first consideration was that the welder produce a tube wire geometry that satisfies both the strength requirements as well as practical production fabrication. In this regard, two different configurations of wire were tried: (1) a diamond shaped spiral wrap with a 1:2 advance ratio with 16 wires in each direction, resulting in a grid slightly under 1/8 in. across the short diagonal and double that in the long diagonal direction; (2) the second technique involves 24 wires displayed axially around the circumference and crossed orthogonally by a single spiral wrap with an advance of 1/8 in. per turn. The second technique yielded the best results and was adopted.

The Machine.

1. Introduction. This machine fabricates a tube of wire grid one inch I. D. utilizing a number of longitudinal wires (the practice has been 24 longitudinals), welded to a wrapped helical wire. Length of the tube is about 8 ft. The helix has a lead of about 1/8" and the longitudinal wires are also spaced 1/8" giving a square mesh.

2. Description. Basically the machine is an adaptation of a lathe, the headstock being used to rotate a copper mandrel forming the inside of the tube and acting as a conductor for the welding current. Surrounding the mandrel is a rotating head, rotating synchronously with the mandrel, containing 24 spools of wire and 24 radially-disposed welding electrodes. These electrodes are spring-loaded and would all contact the mandrel if they were not constrained by a Teflon cam eccentric to the mandrel. This cam allows only three electrodes at the front of the machine to contact the wires at any given time, the center one of these three being energized to produce the weld.

The mandrel is supported mechanically at each end, and two brushholders are also attached to the bed, one at each end, and contact the mandrel with a firm spring load for maximum conductivity of the welding current.

The longitudinal wires are contained on aluminum spools radially disposed on the rotating welding head. They are held in place by spring clips, while another spring applies drag to the spool rim to apply a slight tension to the wire during operation.

The helical nylon thread is contained on a large spool mounted horizontally atop the welder head carriage. From here it is led through guides to the mandrel and wraps around the outside of the longitudinal wires in conjunction with the helical wire for three complete turns before the welding operation occurs. About three inches of this nylon thread wrap is maintained before it is unwrapped from the welded part of the tube by a torque motor.

The helical wire is contained on a spool identical to those used on the rotary head and is mounted vertically alongside the mandrel at a point where the nylon cord is being removed. A spring riding on the spool edge maintains tension on this wire.

3. The Sequence of the Machine Operation

A. Winding The Spools. After having been chosen for the wire size desired, a large spool of this wire is mounted on the cross-slide of a small engine lathe (Fig. 1). A spool from the winder-welder is mounted in the headstock chuck (Fig. 2). The wire is started from the supply spool and guided as winding proceeds (Fig. 3). When the small spool is full, the supply spool is taped to prevent further unwinding and the wire is cut (Fig. 4). When all 25 spools have been filled, the winder-welder is loaded.

B. Loading The Machine. The 24 spools for the rotary head are snapped in place taking care that the axles are centered in their spring clips and the tension clips are bearing on the rims of the spools (Fig. 5). Each wire is then threaded through its hole in the brown phenolic head guide and thence through the inner phenolic guide (Fig. 7). Enough wire is easily pushed through so that it can be picked up on the other side. After all wires have been led through they are spaced evenly around the circumference and taped to the mandrel. The helical wire is wrapped around the mandrel several times then held in place with tape (Fig. 8). The same procedure is then used for the nylon thread (monofilament).

C. Setting Up The Machine. Insert the copper mandrel (1) through the welding head (2) and bring the left end up to the headstock (3). At this point the mandrel is supported on blocks (4). Install the mounting plate (5) on the lathe headstock faceplate using the four bolts provided. Slide the drive gear (6) onto the mandrel. Insert the mandrel's end into the mounting plate. Line up the drive gear axially with the two transfer gears (7) then tighten the two set screws (8) into their corresponding depressions in the mandrel. Make sure the brush assembly (9) is riding firmly against the mandrel.

Replace the tail stock (10) and limit switch (11) using the bolts provided. Tighten tailstock screw (12) snugly into the outboard end of the mandrel. Now the supporting blocks (13) at each end can be removed.

Return the carriage and welding head to the headstock end of the machine, and engage the carriage apron half-nut (14). Install the center steady-rest (15) and using a screw-driver, position the rollers (16) to remove all the sag from the mandrel. Check at this point for level all along the mandrel. Check right-hand brush assembly (9) for good contact.

Going now to the welding head, remove the tension from the five electrodes nearest you, using the L-shaped tools provided (17).

D. Running The Machine. Remove the five L-shaped tools holding the electrodes away from the mandrel. Start the machine and run about two inches of tubing. Remove the taped end of nylon monofilament and attach to take-up spool (18). The machine may now be run until the welding head nears the center support rest. At this time the center rest may be safely removed and the machine may continue to run until it has reached the right-hand limit switch (19) which turns the machine off.

While the machine is running examine the welds through the microscope (20) for visual evidence of weld quality. By attempting to move the welded wires with the soft pad of the fingers another indication of weld quality is obtained.

E. Adjusting The Welding Current. If there is visual evidence of excessive heat at each junction, reduce the current, using knob (21) on the power supply. A typical group of settings for 5-mil stainless steel heat-treatable wire would be as follows:

Pulse Length--Seconds	0.1
Variable Pulse Length	Between 9 and 10 o'clock
Transformer Tap	4
Energy Control	Between 1 and 2 o'clock
Push-to-read (Voltage)	48
RPM	4

The above settings apply to the Weltek Model AC-10 Power Supply built by Wells Electronics, Inc., South Bend, Indiana.

F. Removing The Finished Tube. In general removing the mandrel from the machine is the reverse of the set-up procedure. The limit switch bracket and the tailstock are removed from the outboard end of the mandrel using blocks to support the end of the mandrel. The welding head is moved to the head stock end of the machine, after the lifters have removed the front five electrodes from contact with the tubing, and the severed wires have been taped to the front bracket (22). The mandrel is removed from the machine to the transfer jib (23). The end of the mandrel is centered with the end of the transfer rod (24) and the mandrel is then clamped in place (25). It will now be found that the tubing is too tightly wound on the mandrel for easy removal. Recalling that the circumferential wire is a helix, start at each end and slightly "unwind" this helix (26). Working from the ends, continue this slight unwrapping until the tubing is loose on the mandrel. At this point the finished tubing is gently slid from the mandrel to the transfer rod (27), the mandrel clamp is loosened and the mandrel is returned to the machine for the next run.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Spacetube.

1. The tubular metal mesh. There is no doubt that the state-of-the-art of ultra-light-weight reflecting structures has been decisively extended by the materialization of this metal mesh. The presence of a weld at each crossing of the fine wires reduces the point-to-point electrical resistance to an acceptably small value while increasing the mechanical strength of the structure. The work-hardened steel structure is stiffer and stronger than the aluminum foils which have hitherto provided the reflecting surface of passive communications satellites.

For demonstration samples wire diameter of 0.002 in., and tube diameter of 1 inch and length of 6 feet with a lattice spacing 1/8 inch azimuthally by 1/8 inch axially proved to be satisfactory. The wire diameter is easily adjusted upward, and the other dimensions of the samples can conveniently be opened by modification of the automatic welding machine. Stainless steel type 347 is proven as an appropriate material. As the present conclusions are written there is at hand a sample 3 feet long: it is measured to weigh 0.74 grams (±10 milligrams, probable error), and the central sag, when the tube is simply supported as a beam in the laboratory gravitational field, is about 1 millimeter. (8 foot lengths of tube, made from 0.005-inch wire, sag about 3/8 inch when simply supported.)

2. Liner. It is a conclusion that a polyethylene liner for the tubular mesh work, gas tight for the purpose of inflating and distending the mesh to the shape of a pressure-stiffened cylinder, will subsequently fuse and withdraw onto the metal mesh if exposed to temperatures between 160 and 200°F. These would be the equilibrium temperatures of a sunlit orbit. The withdrawal is such, in the laboratory, that the frontal section presented by the distended tube to drag forces is reduced by a factor of 99.

The Automatic Welder. It is a conclusion that the SSS Winder-welder works, unattended, making a weld invariably at each crossing of the fine wires. Wire sizes $0.002 < d < 0.005$ do exhibit this perfection of weldment, and no reason is known why larger gauges of wire cannot be used. The tube diameter of the samples is 1 inch which can be varied by the adoption of a larger or smaller mandrel. The spacing of axial wires in samples has been 1/8 inch which can be changed by adding or deleting feed spools. The helical advance is variable with faceplate change and the dimensions of tube produced are thus adjustable to requirement. The production of the sample tube has been at about 1 inch per minute.

A planar mesh. On the outside skin of any passive reflecting satellite there may be a mesh, planar in the first approximation, of metallic conductors at a spacing dictated by the wavelengths of interest. The Spacetube set forth above can be slit along one generator and developed into a plane strip about 3 inches wide. There is no foreseeable difficulty in making 4-foot wide planes with continuous lengths, and the process need not be costly because automatic welding has already been demonstrated. It is thus a conclusion that the art of such a plane mesh exists. There would not be a problem of deforming such a plane to conform to radii of curvature of 100 or 200 feet.

Test assembly. SSS fabricated and shipped all the elements of an assembly which can be fitted to a 22-foot torus so as to be electrically tested for its reflecting performance. Briefly, a multiplicity of tubes, each of which serves as a member of a space truss, is fitted to an inflated skin which distends to a radius of curvature of 200 feet, there being a special joint at each point in the configuration where two or more tubes come together.

Potential advantages. The development effort has not uncovered any weak point among the potential advantages listed at the beginning of the present report, but has rather gained the demonstration of improved stiffness-to-weight for all those applications where lightweight is desired and relatively low absolute stiffness is required.

Recommendations

An improved passive communications satellite. The advantages of a lightweight space truss as the fundamental structure for a passive communications satellite are more outspoken than they were before the present development effort was undertaken, and this development should be continued. Special emphasis is needed on the folding, packaging, unfolding and inflation behavior of the Spacetubes. It is envisioned that a launch to orbit could be confidently underwritten after about one year of further development.

Improved extensive structures in space. There should be a study made of all NASA requirements for large unmanned satellites with a view toward further applications of Spacetube. Especially important appear to be long booms and large aperture antennae.

APPENDIX 1

The Contract in a Nutshell, and The Shifts in Emphasis and Scope

The Contract NAS5-3964 was entered into by GSFC and SSS on June 19, 1964 for "Advanced Geodesic Design Passive Communications Satellite Study." There were six tasks and four deliverable items:

Tasks

1. Study braided aluminum module construction of an extension system for a 425-ft. sphere of cold-welded aluminum mesh
2. Fabricate and test sample tube elements
3. Fabricate a segment of the sphere 14 to 22 ft. across
4. 8 man-days of engineering at GSFC in test of segment
5. Fabricate a 2-1/2 ft. scale structural sphere
6. Report all the foregoing results

Items		Deliverable
1.	The segment of Task 3,	5 months
2.	The model of Task 5,	5 months
3.	Progress reports,	monthly
4.	Final project report,	15 days after Task 4

Modification No. 1. The change became effective December 18, 1964 in the sixth month of the contract. Stainless steel wire was substituted for both aluminums in Task 1, and the delivery of Items 1 and 2 was set at 3 months from the effective date of the modification.

Modification No. 2. The change became effective July 8, 1965 in the thirteenth month of the contract. The spherical segment of Task 3 and Item 1 was increased to 26 ft. diameter on a radius of curvature of 200 ft., Task 4 was at the appropriate facility rather than necessarily at GSFC, Task 5 and Item 2 were deleted. There were added Tasks 7 and 8 and Item 5:

Tasks

7. Fabricate welded stainless steel electromagnetic reflective mesh 26 ft. in diameter, 200 ft. in radius of curvature, to go with the revised segment of Item 1.

8. Studies of the structural deflections, temperature profiles, packaging and unfolding sequences, inflation sequence of the system.

Item		Delivery
5.	The stainless steel mesh of Task 7.	16 weeks from ATP

Tasks 7 and 8 and Item 5 were made subject to a "stop work order" under which there were to be no costs incurred until 90 days had elapsed, unless the contract had been re-activated earlier by the cancellation of the stop work order.

Modification No. 3. The change became effective July 16, 1965 and simply added NASA's most recent procedures (December 15, 1964) of industrial property control to the contract.

Modification No. 4. The change became effective August 17, 1965 and simply corrected a typographical error of $314 for $414 for equipment rental.

Modification No. 5. was a "no cost settlement agreement partial termination" entered into October 12, 1965. Tasks 7 and 8, along with deliverable Item 5 were terminated from the contract.

Modification No. 6. (January 25, 1966) changed the delivery of Item 1 and required that it be delivered by May 31, 1966.

Modification No. 7. (April 21, 1966) established the identity of a newly cognizant technical officer at GSFC.

Modification No. 8. (November 21, 1966) acknowledged a cost underestimate and accommodated completion of the final report.

Modification No. 9. (December 13, 1966) was issued to correct an inadvertent error of no material significance in Modification No. 8.

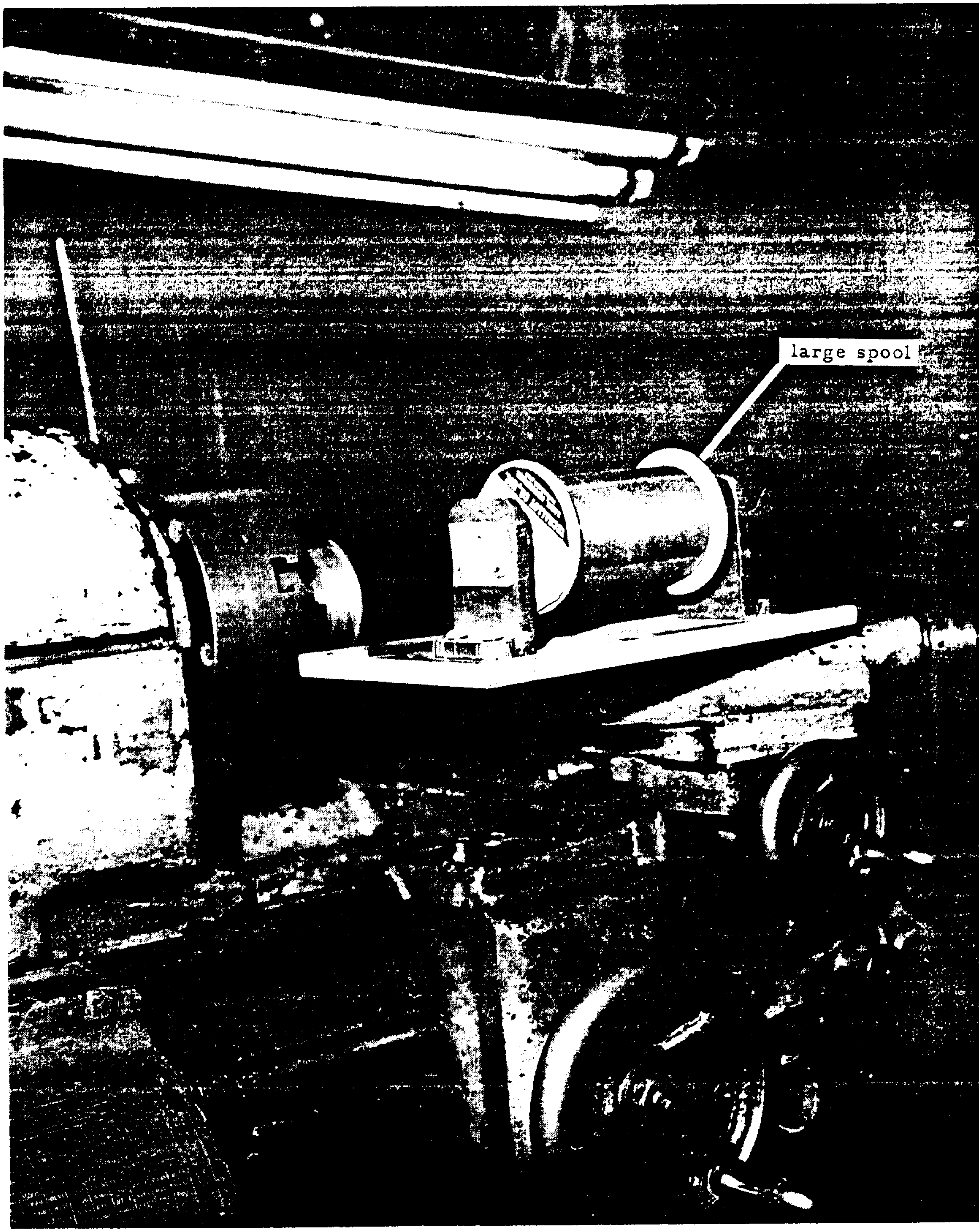


Fig. 1

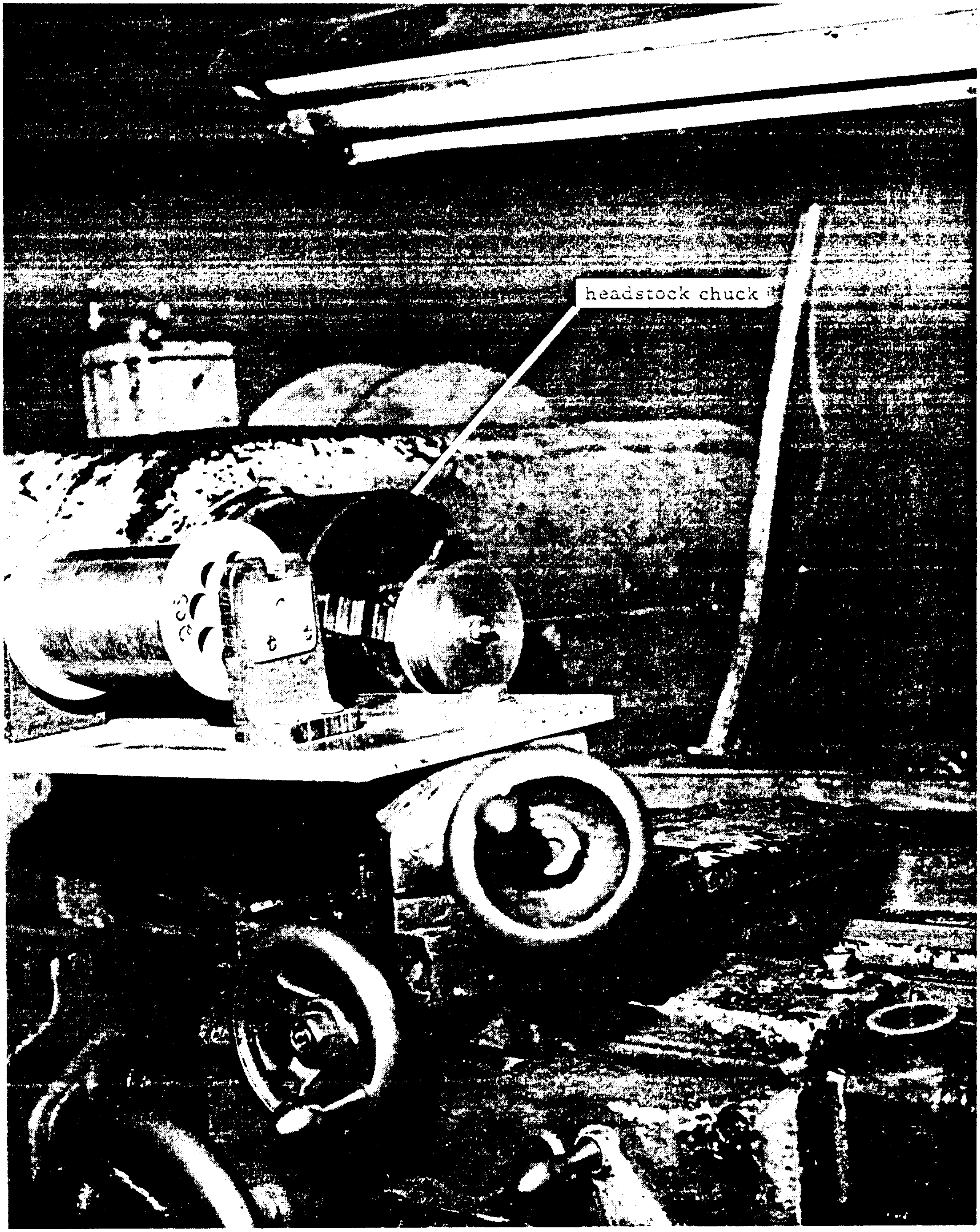


Fig. 2

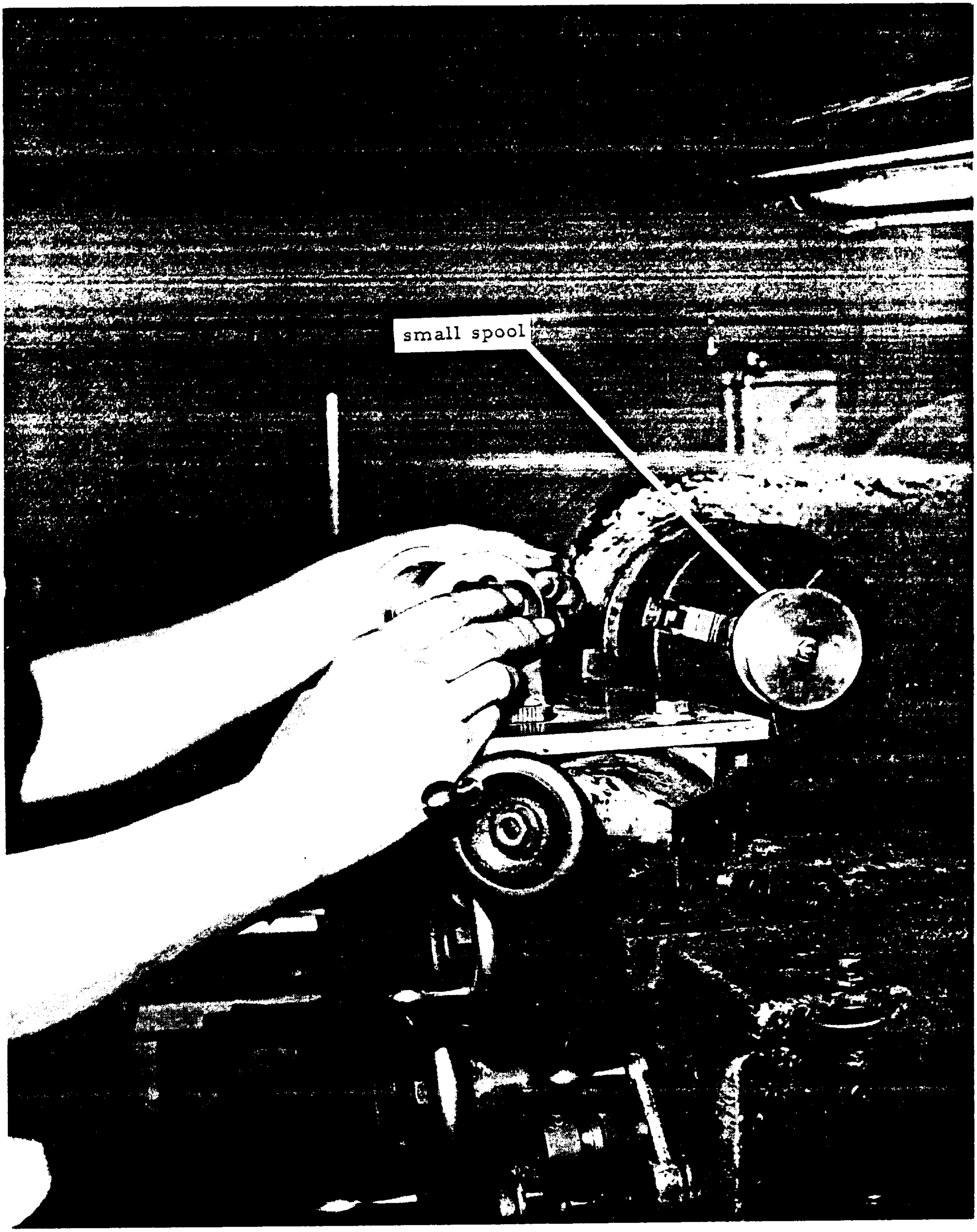


Fig. 3

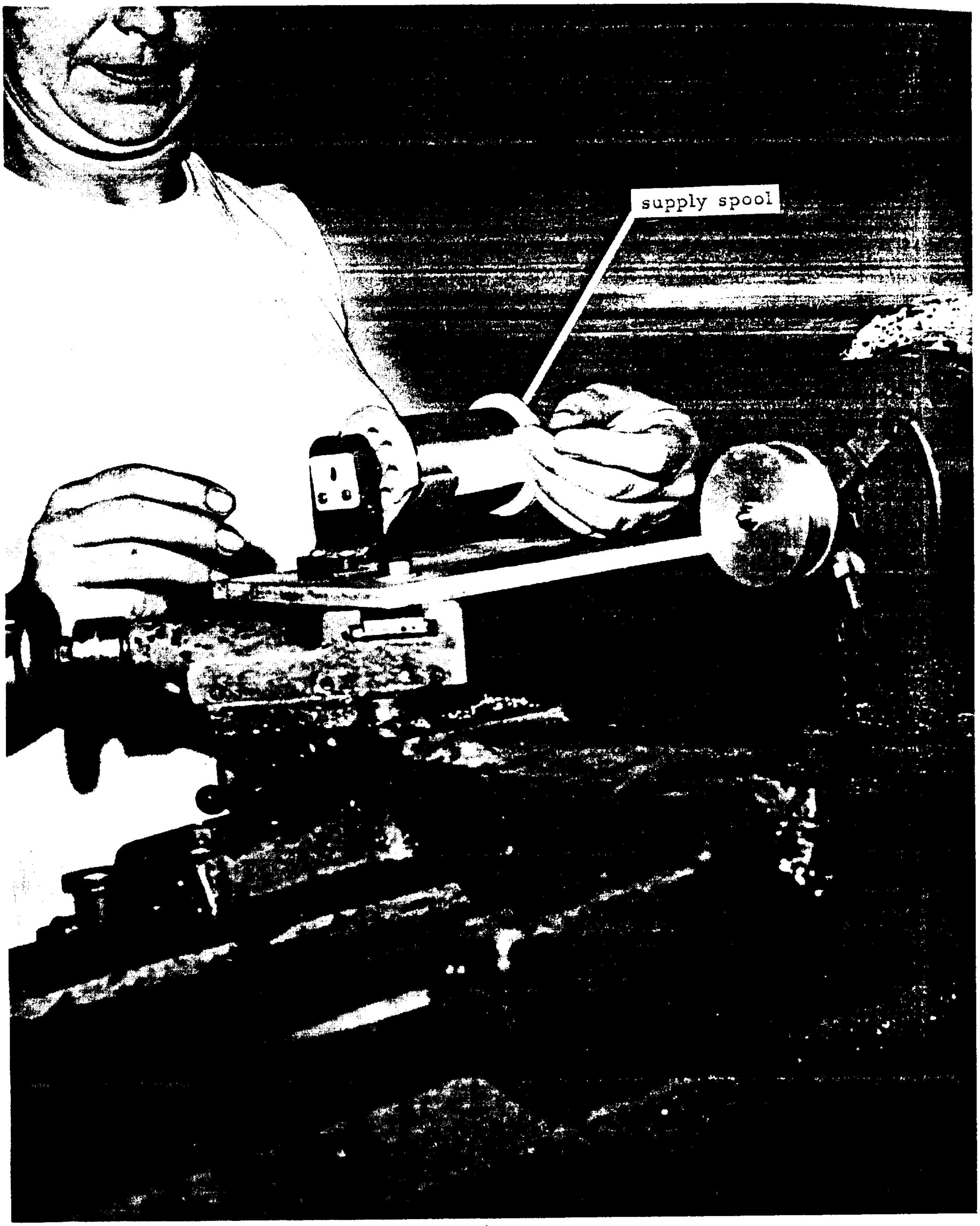


Fig. 4

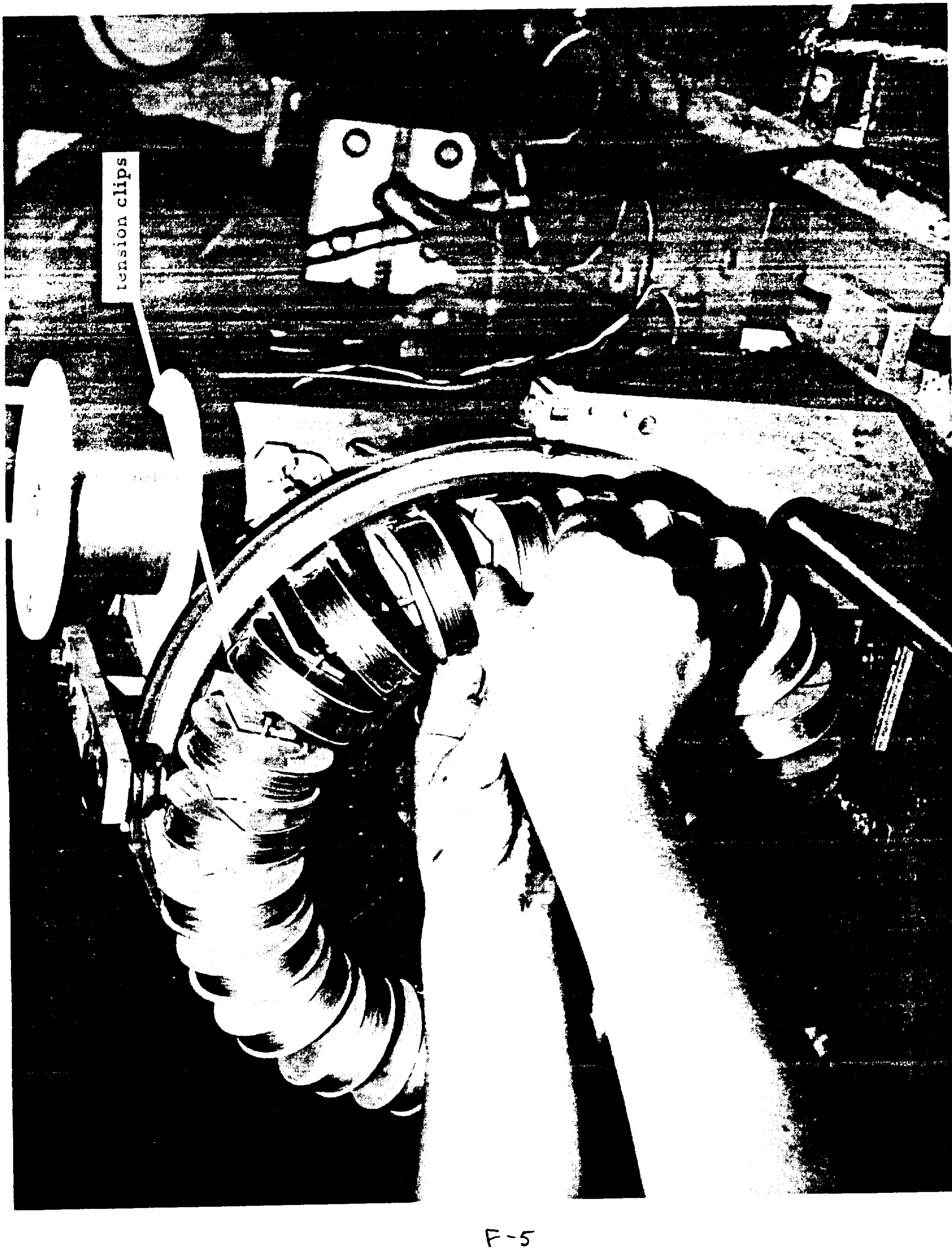


Fig. 5

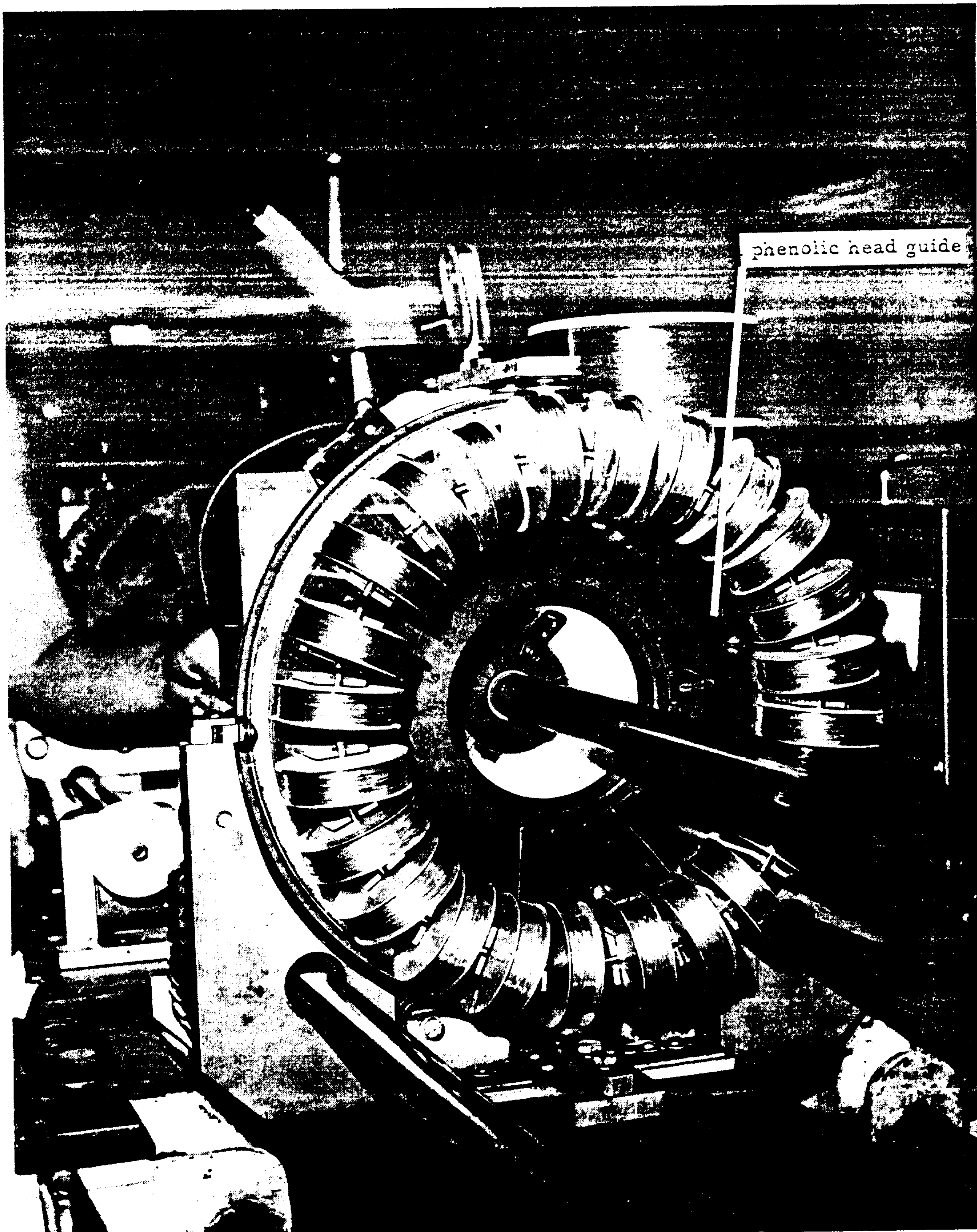


Fig. 6

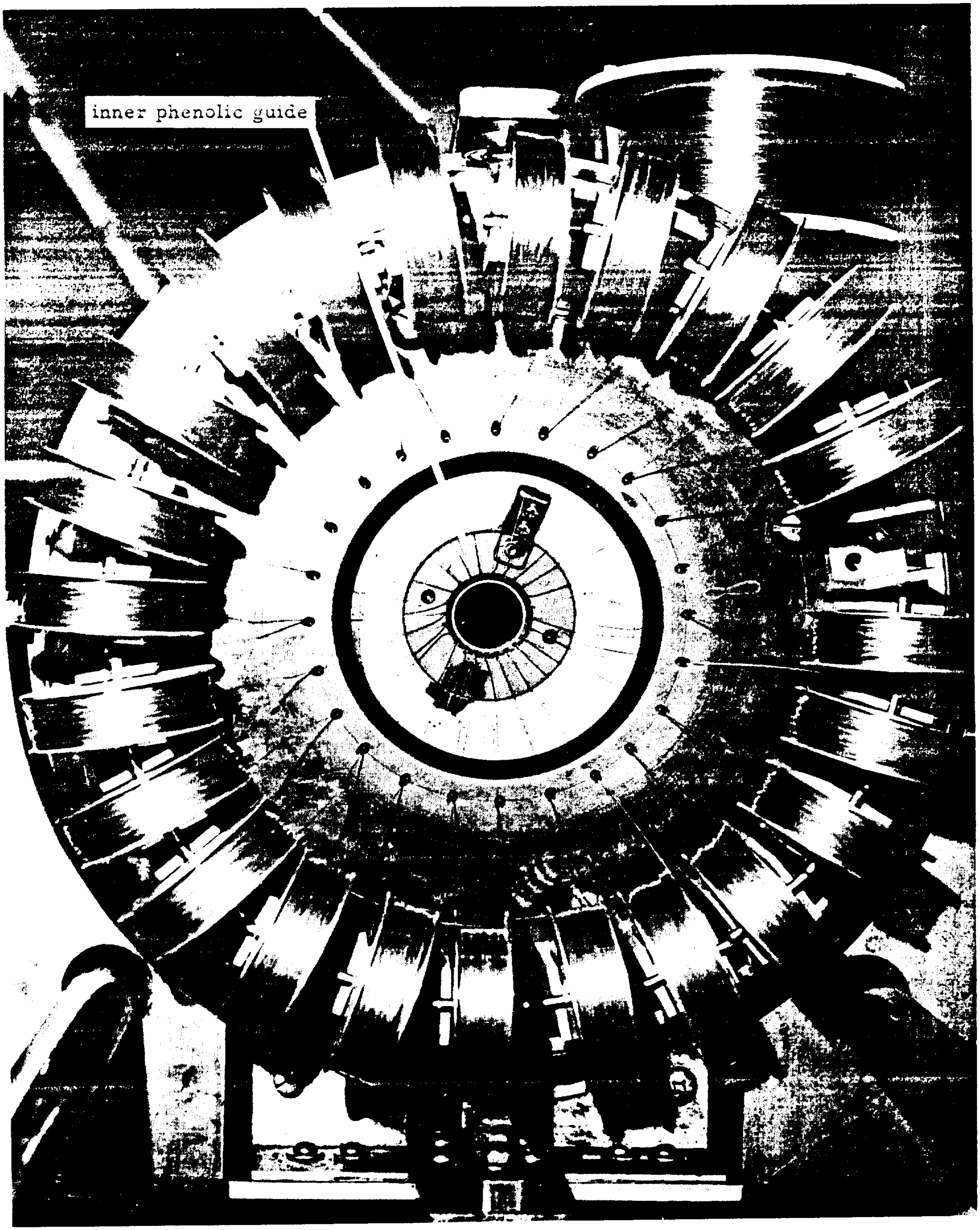


Fig. 7

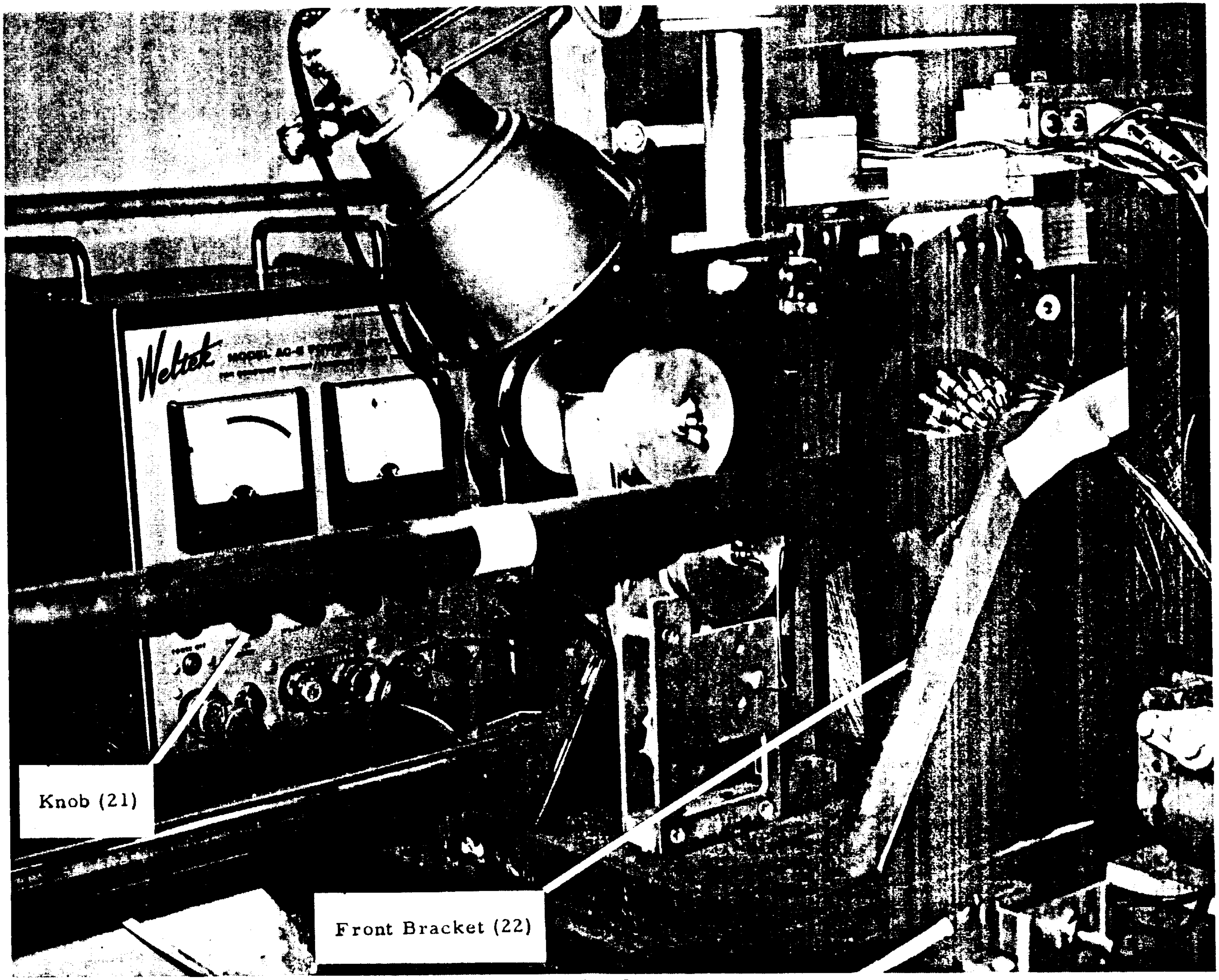


Fig. 8

Fig. 9

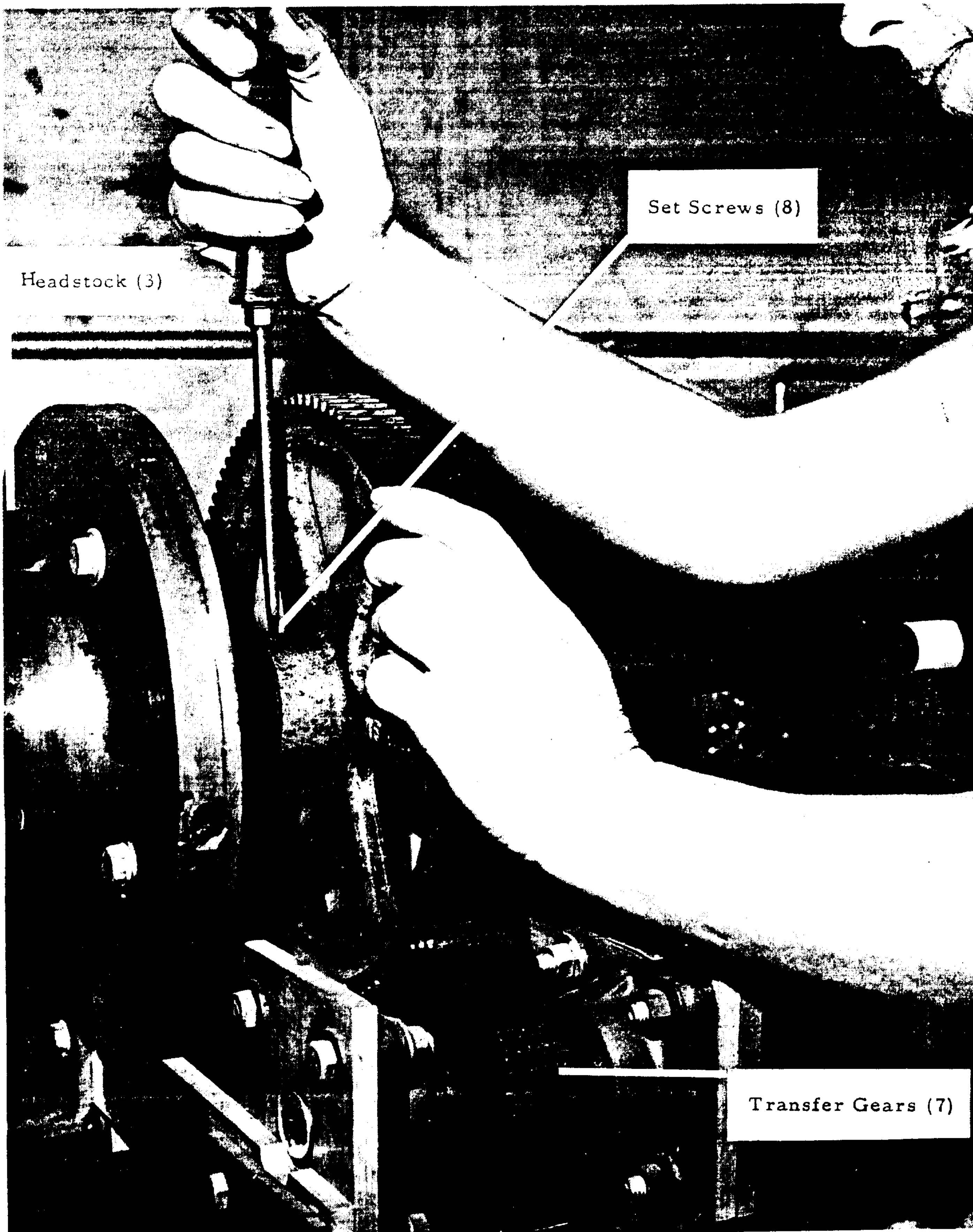


Fig. 10

Fig. 11

Fig. 12

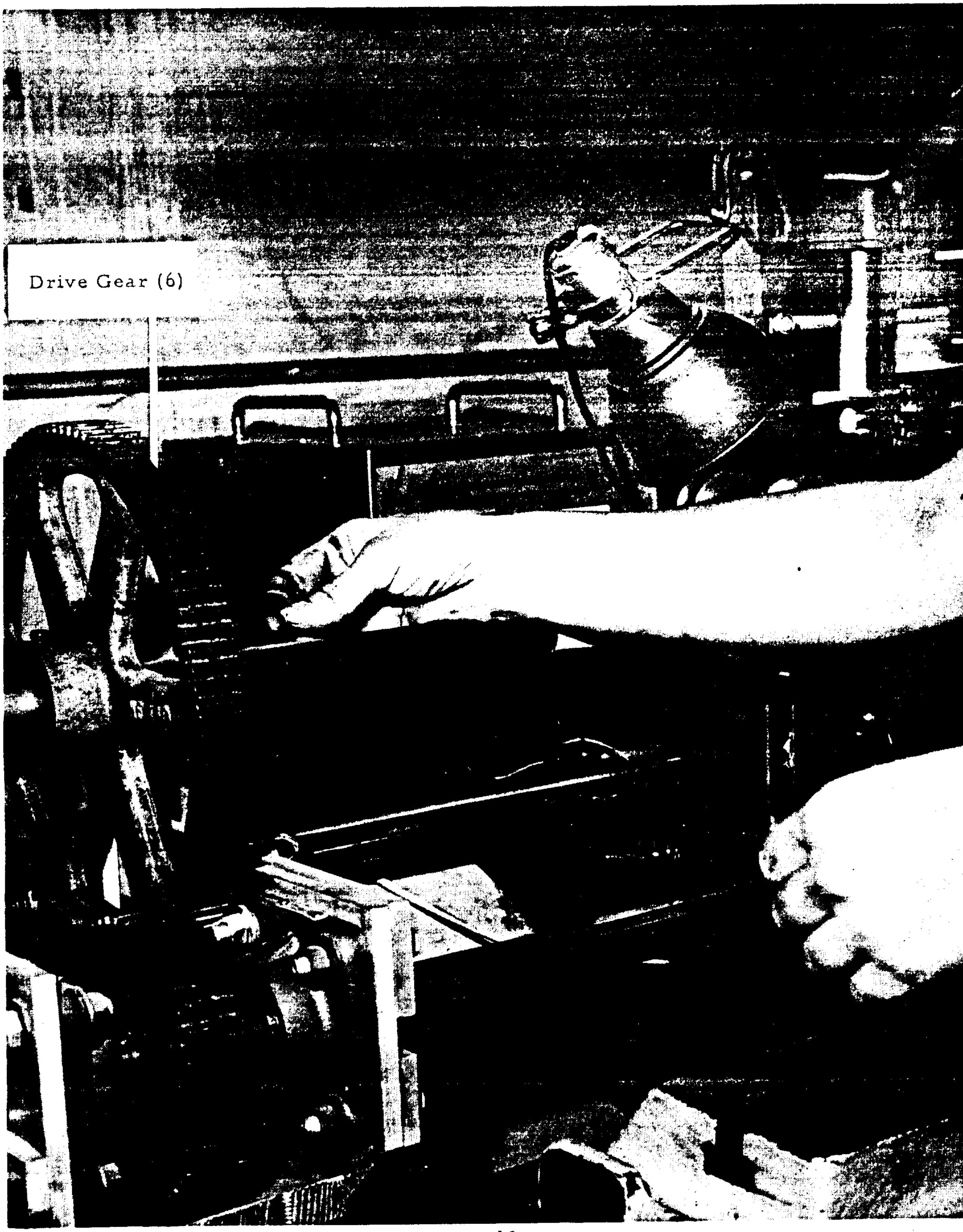


Fig. 13

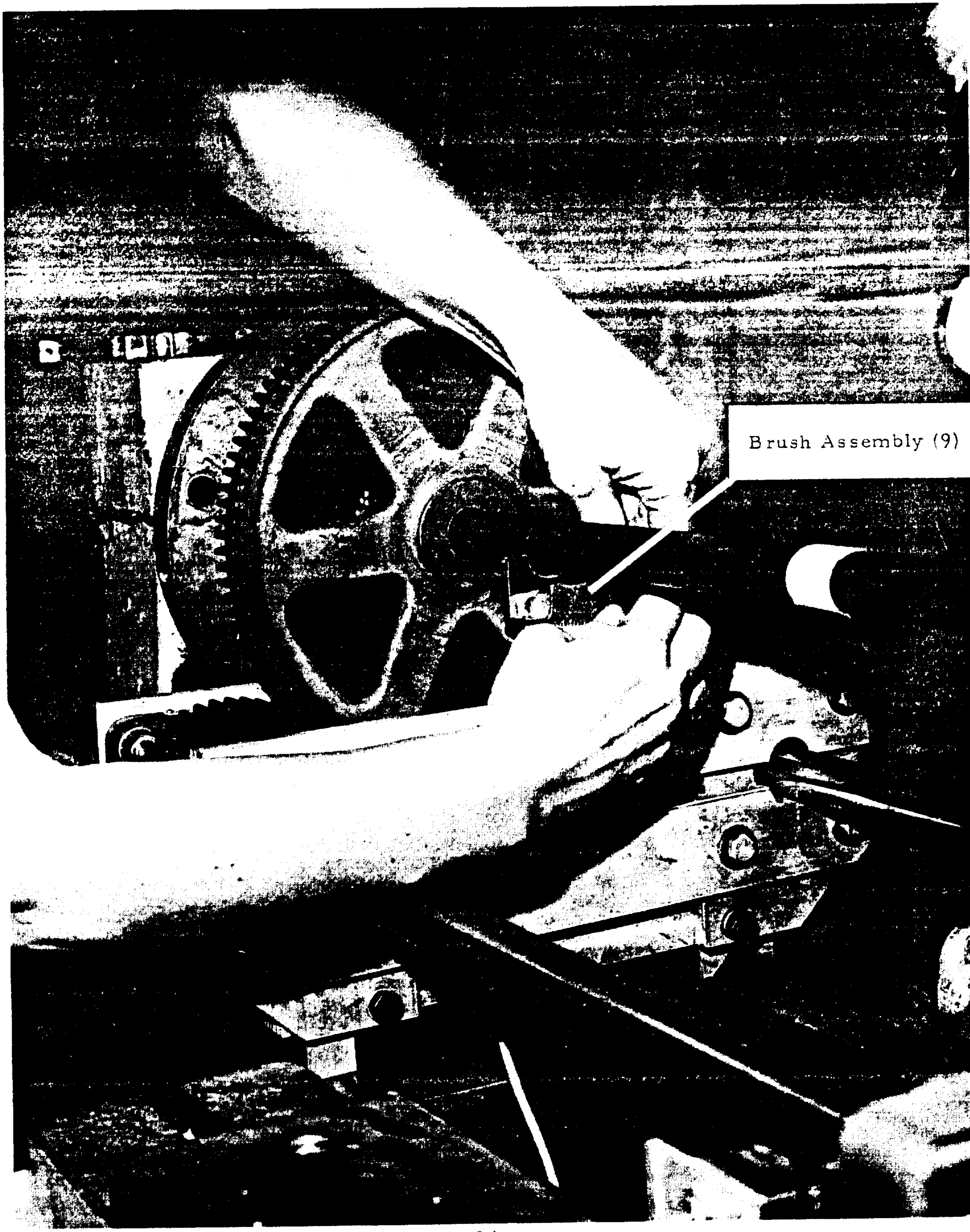


Fig. 14

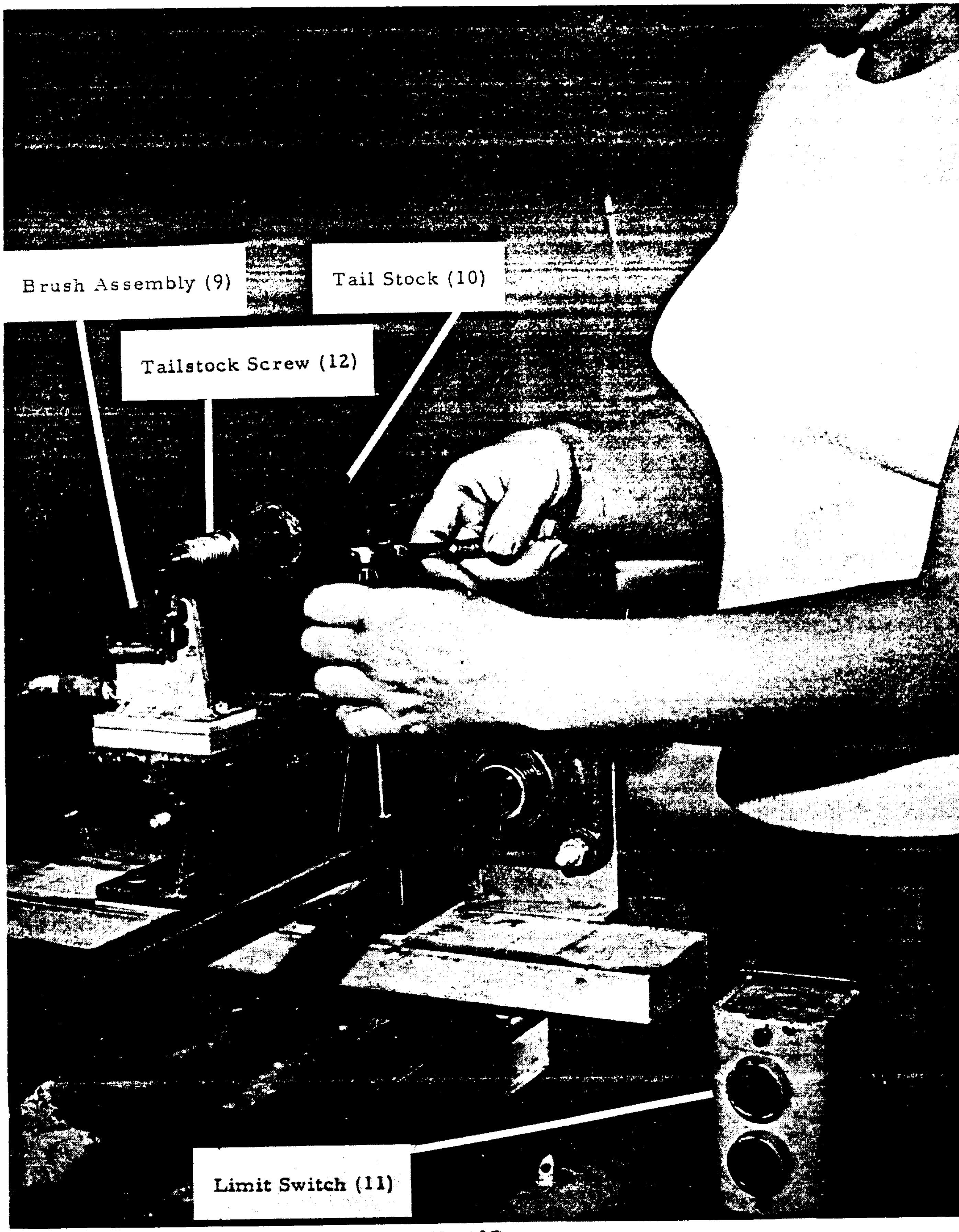

Brush Assembly (9)
Tail Stock (10)
Tailstock Screw (12)
Limit Switch (11)

Fig. 15

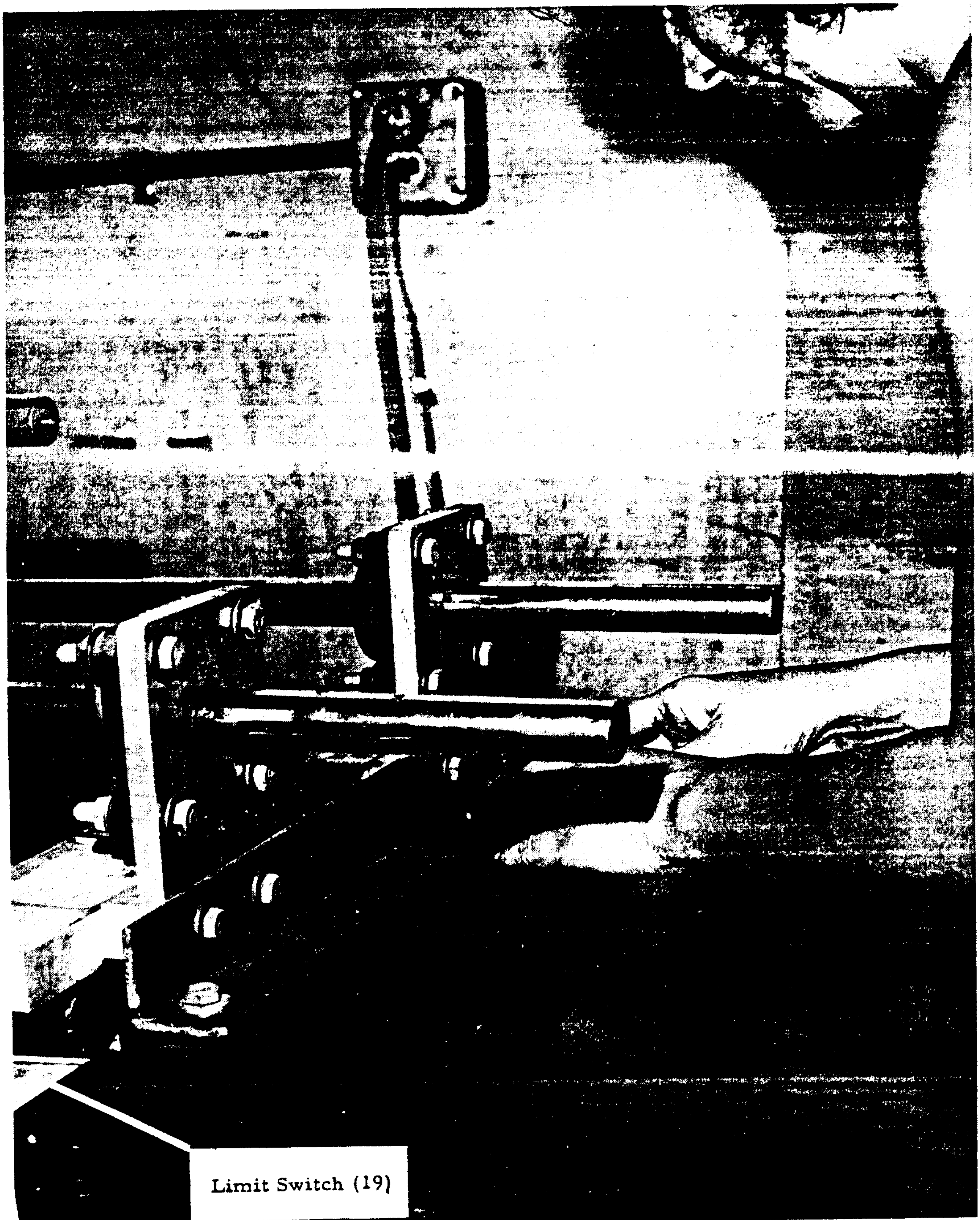


Fig. 16

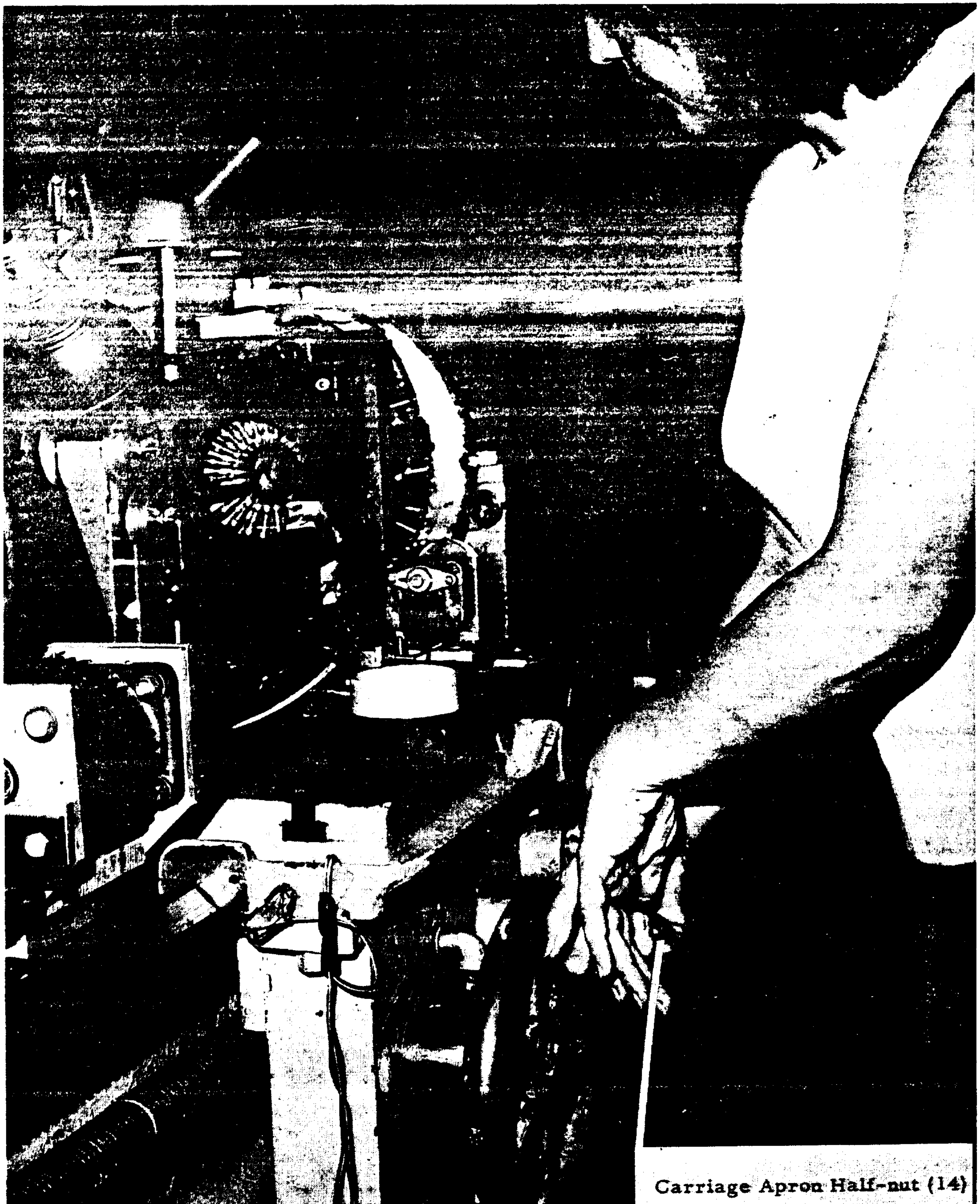


Fig. 17

Fig. 18

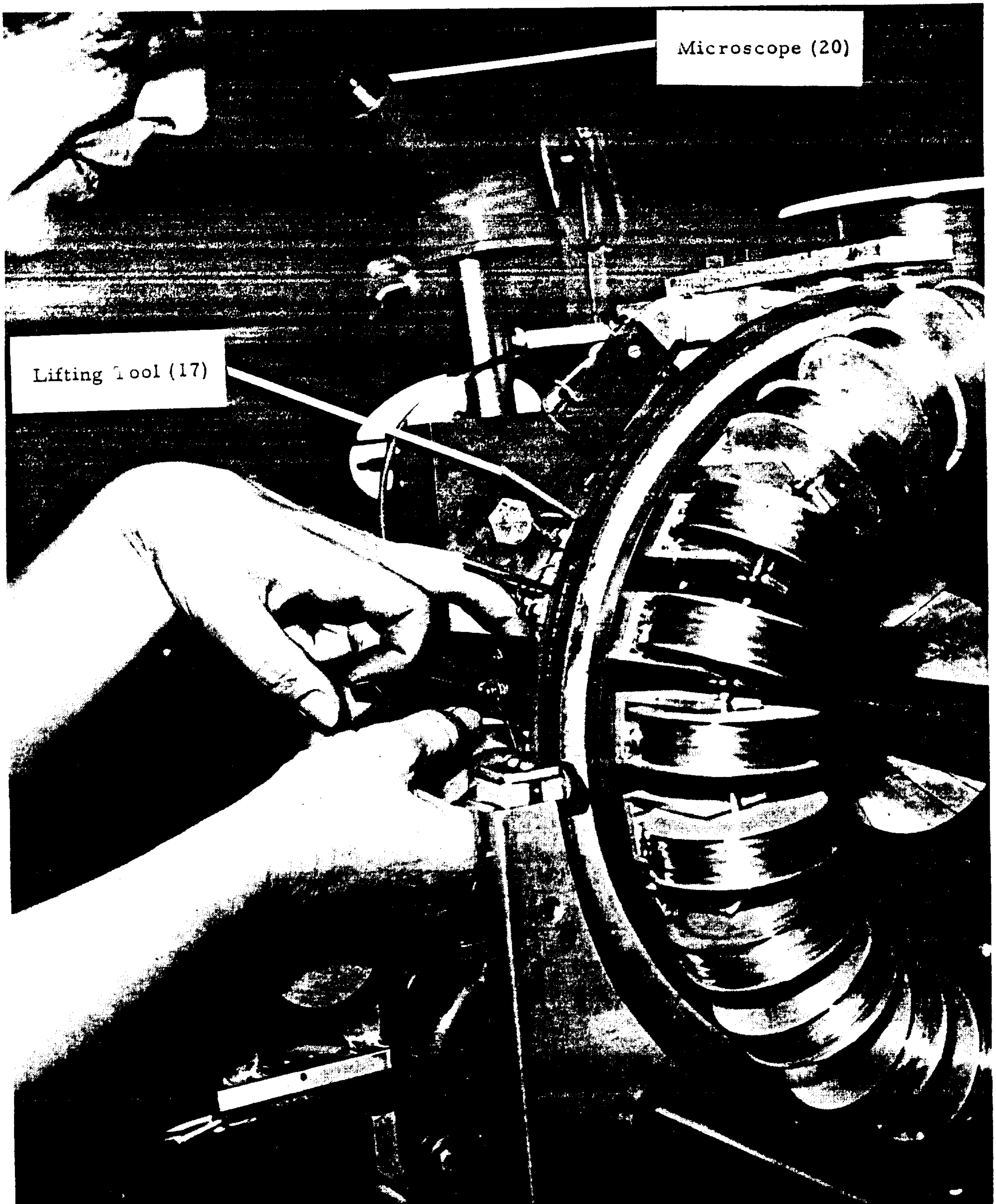


Fig. 19

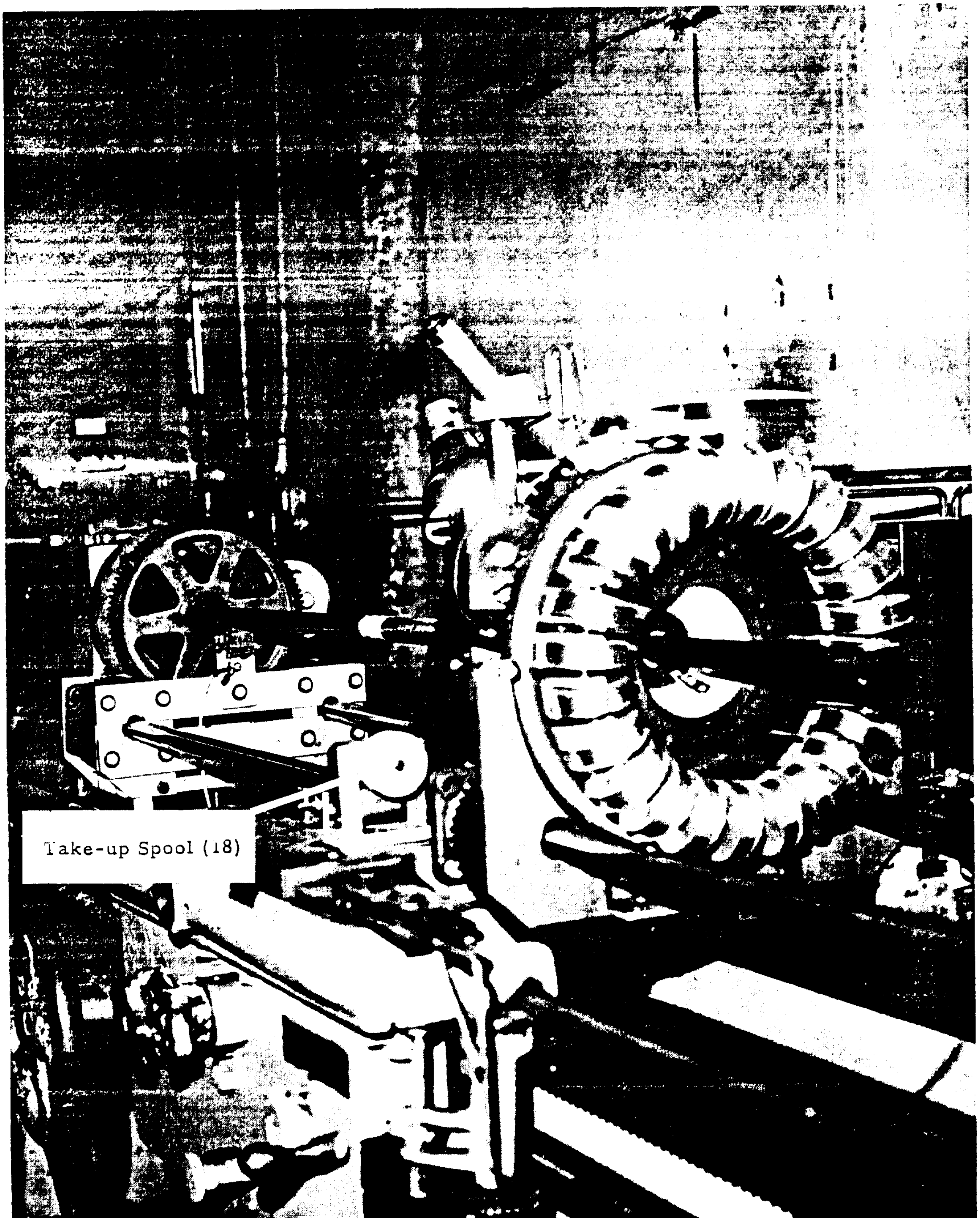


Fig. 20

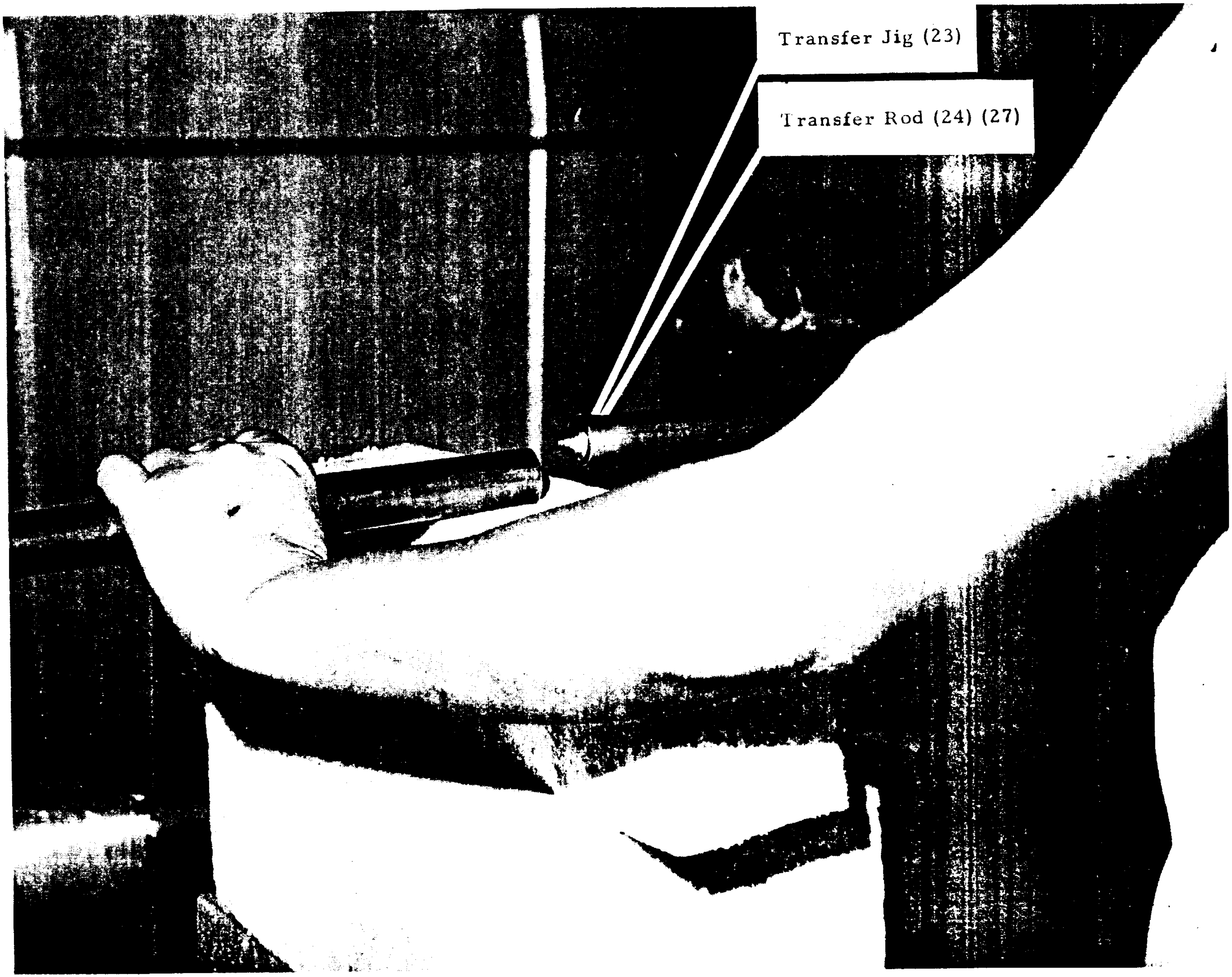


Fig. 21

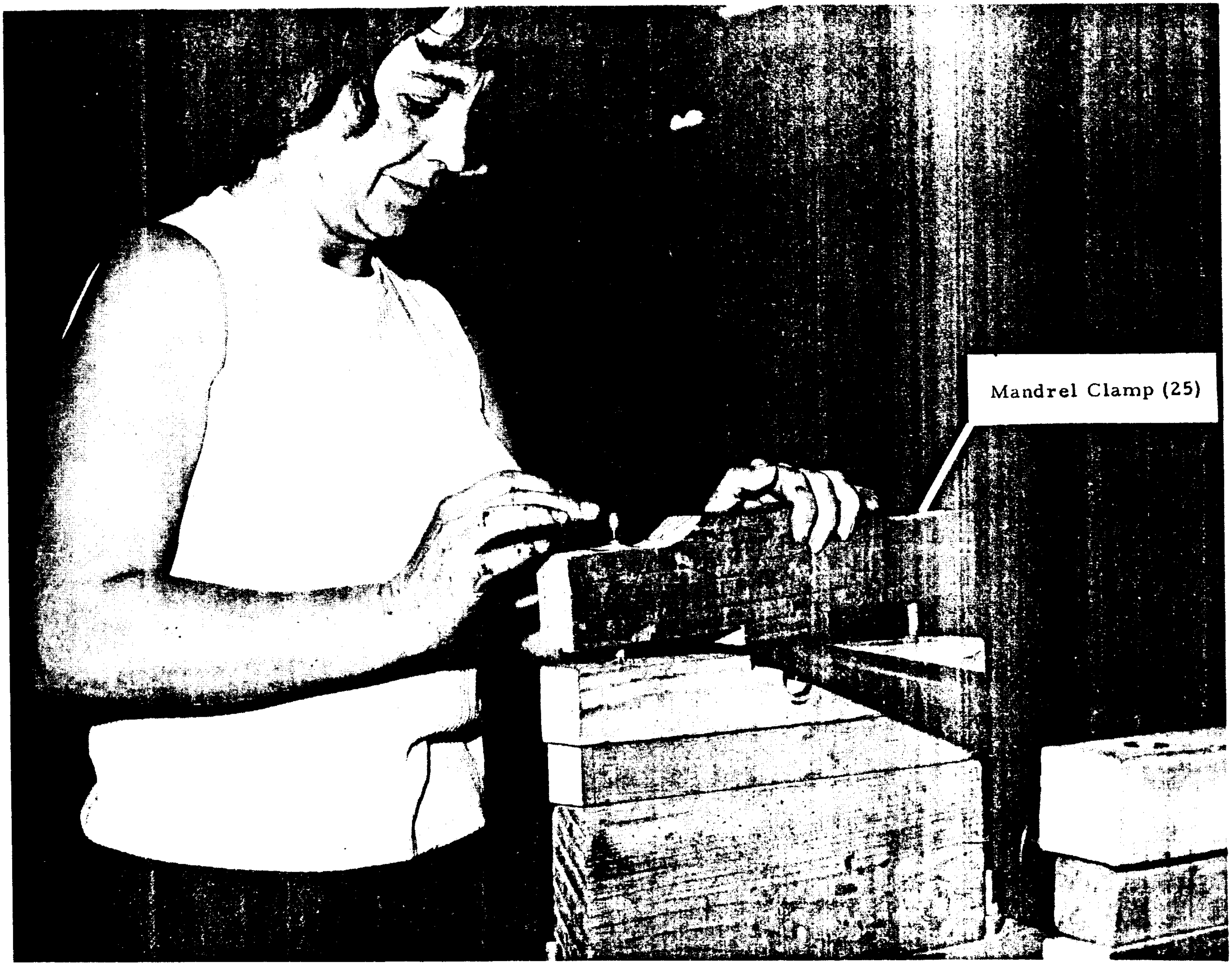


Fig. 22

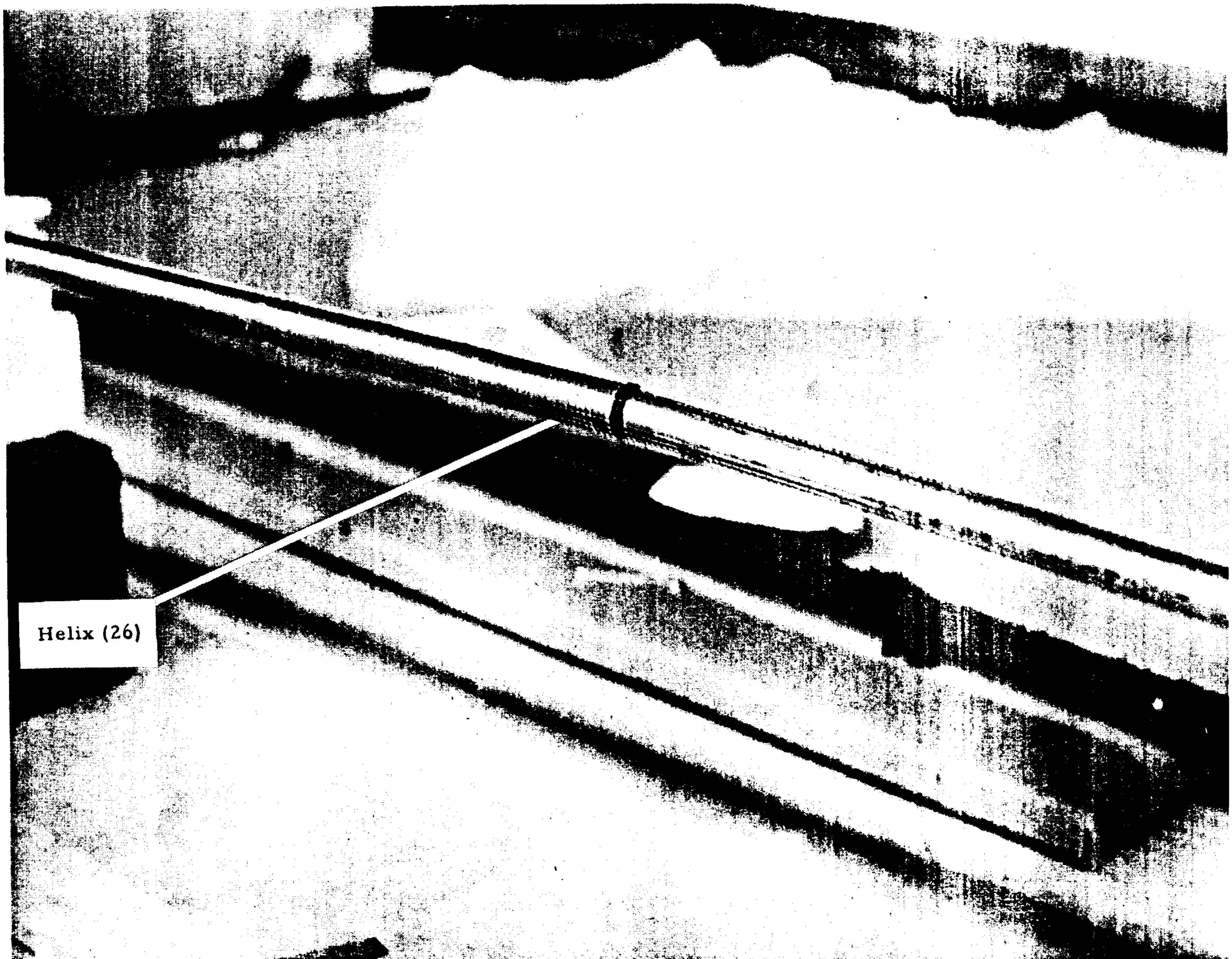


Fig. 23

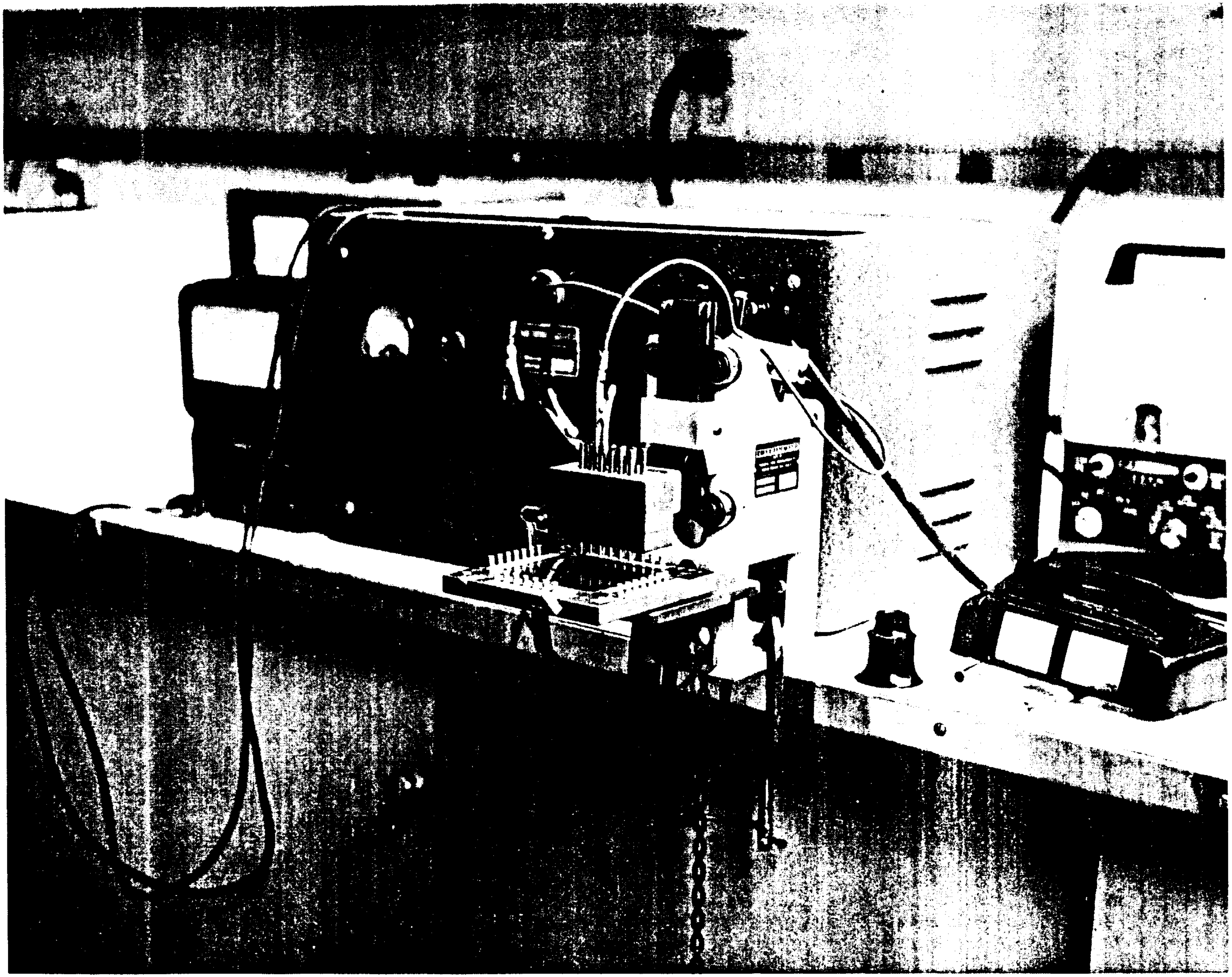
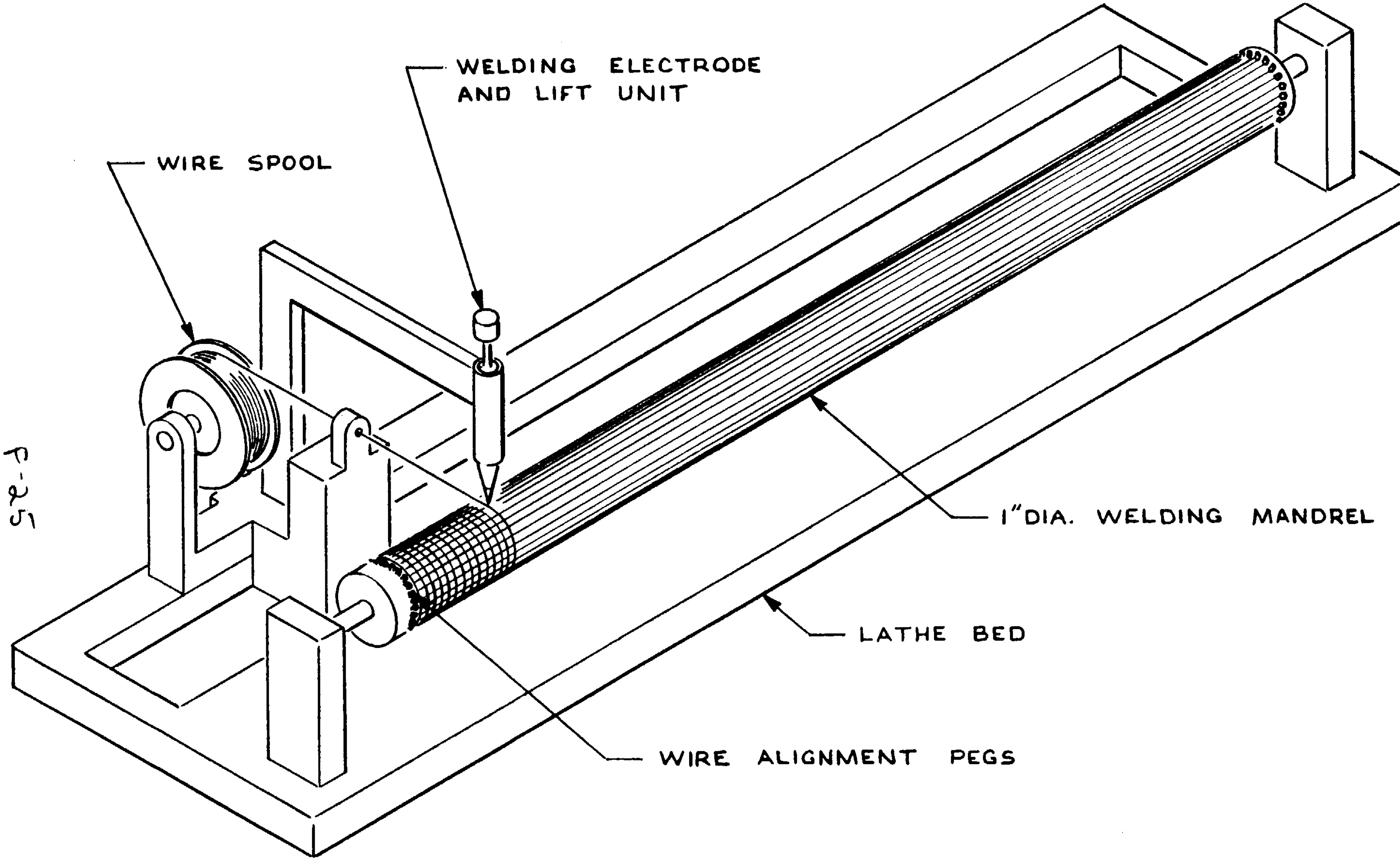


Fig. 24 The 13-Electrode Welder



EXPERIMENTAL WELDING FEASIBILITY MODEL

Fig. 25 Single-Electrode Welder

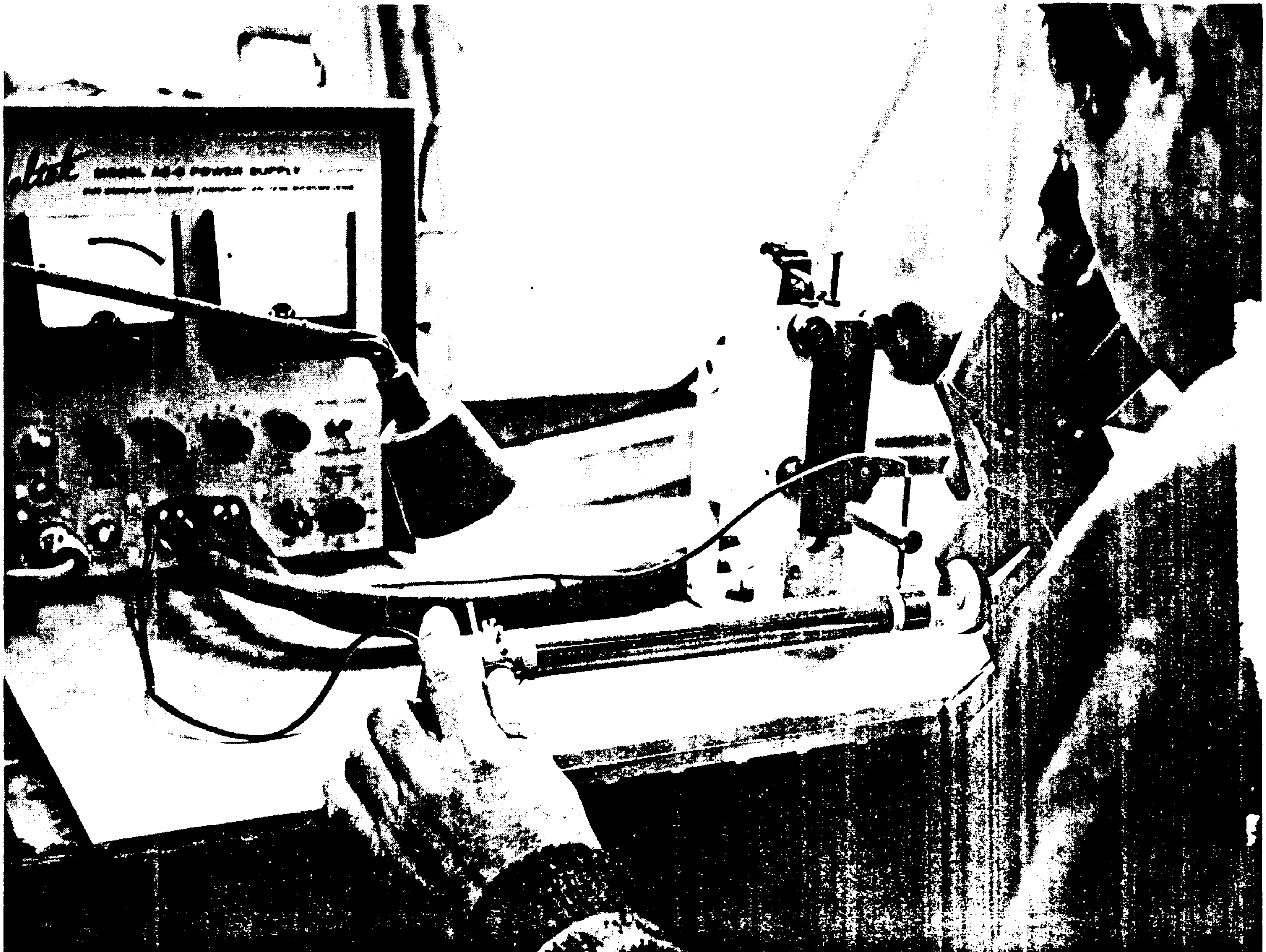
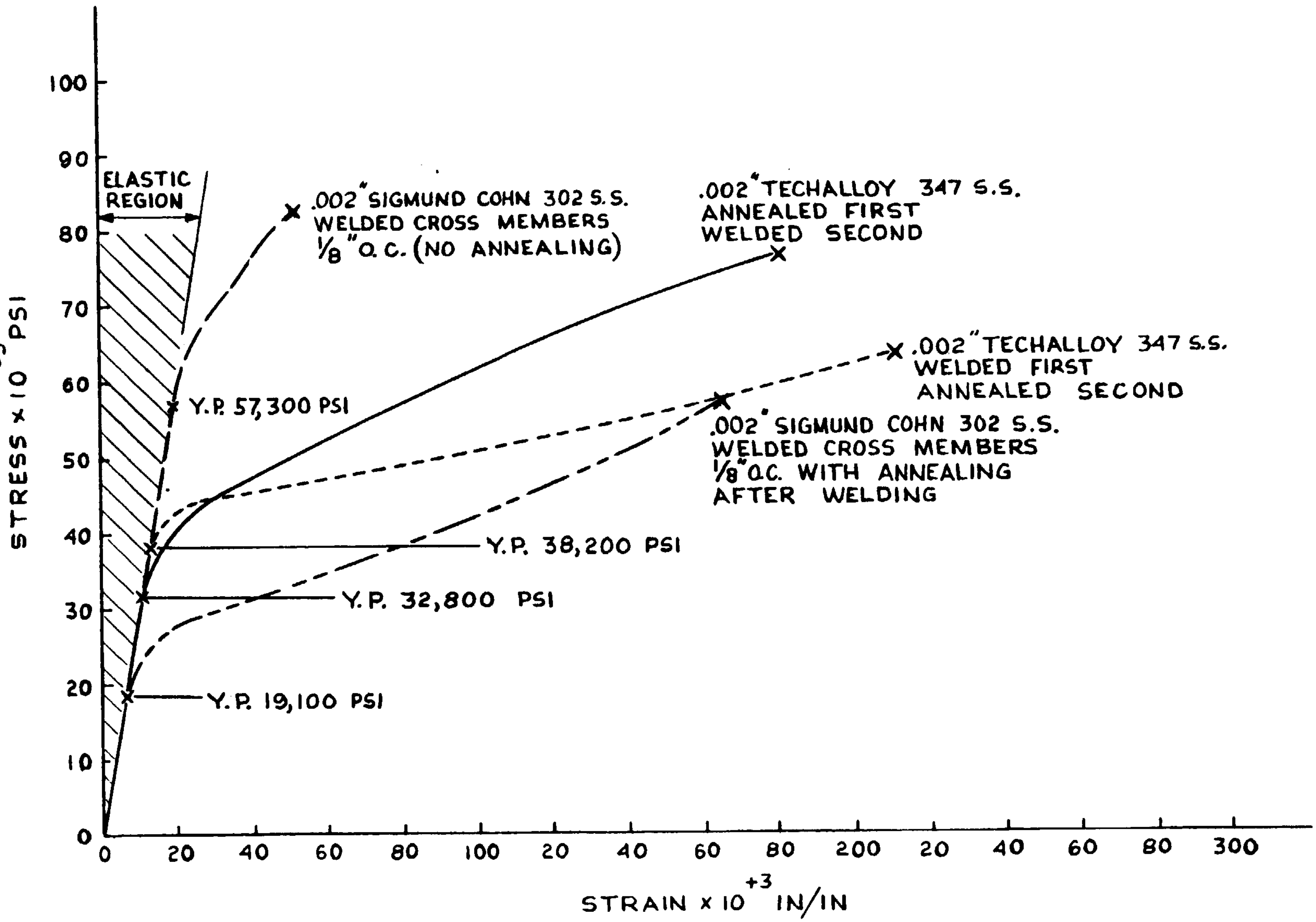


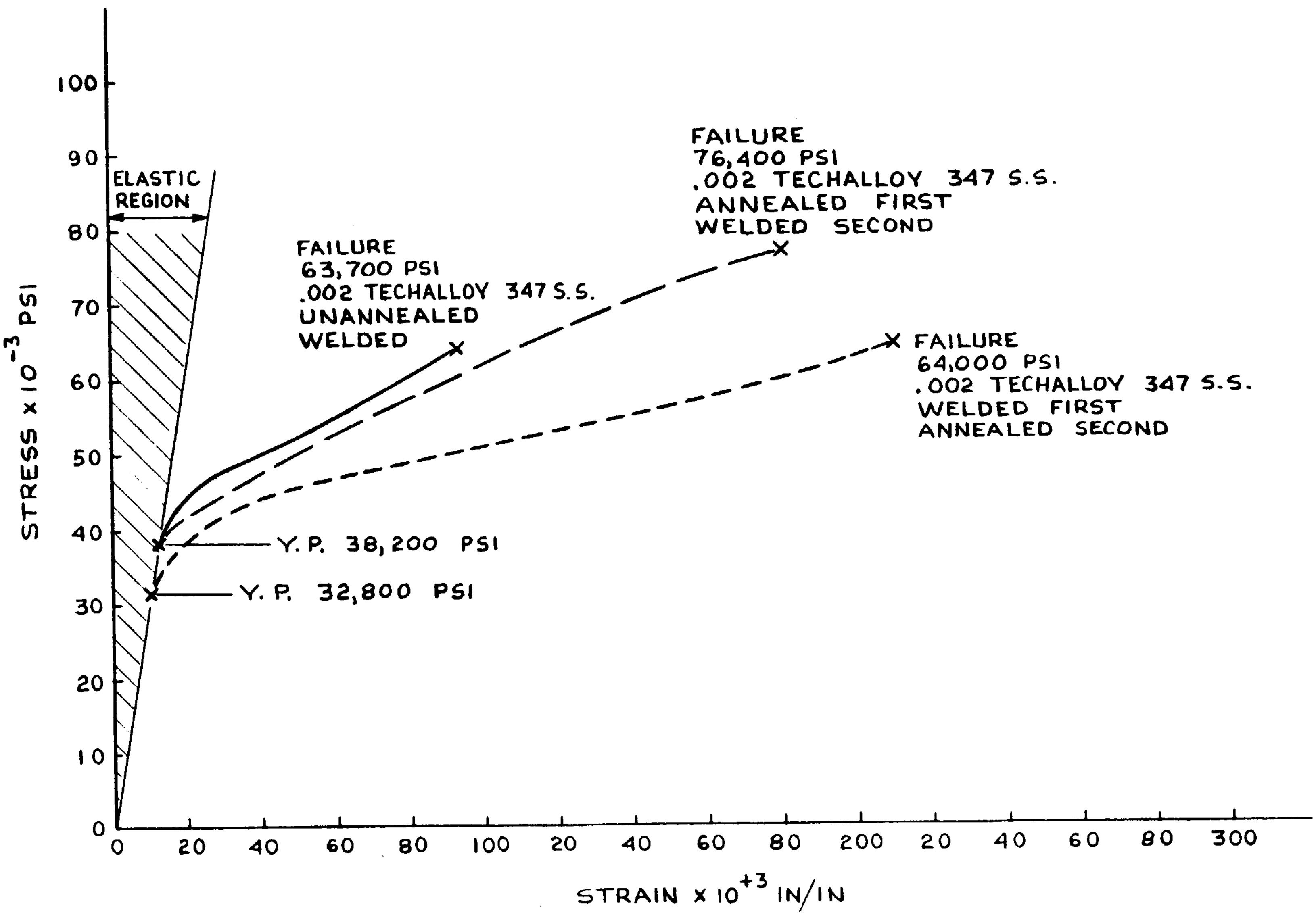
Fig. 26 Single-Electrode Welder



ANNEALED WIRE ANALYSIS

Fig. 27 Graph of Stress-Strain Curve

F-27



TECHALLOY 347 STAINLESS STEEL WIRE ANALYSIS

Fig. 28 Graph of Stress-Strain Curve--302, 304

F-28

Fig. 29 Short Test Module

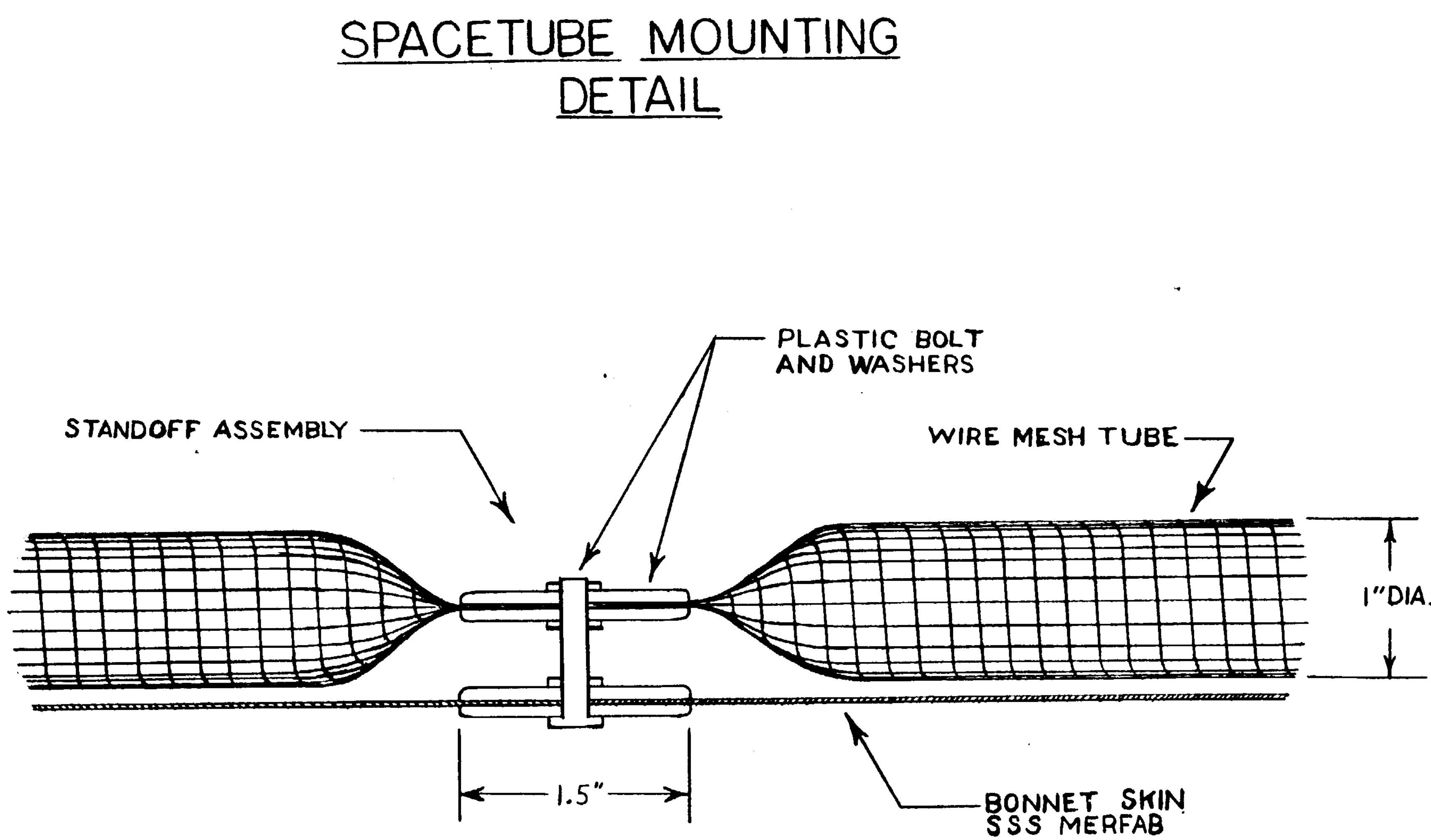


Fig. 30 End-Closure Device

BONNET GEOMETRY

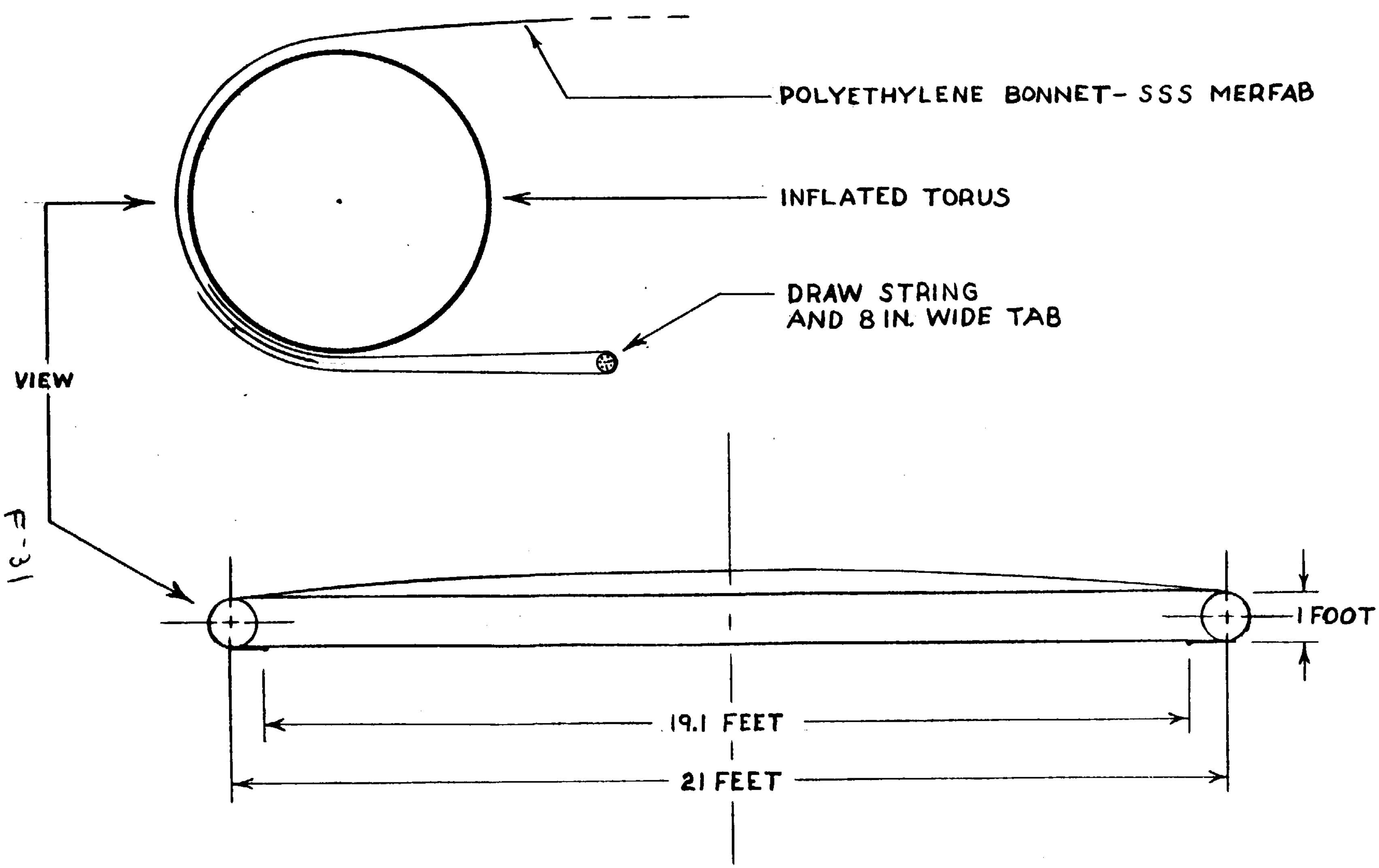
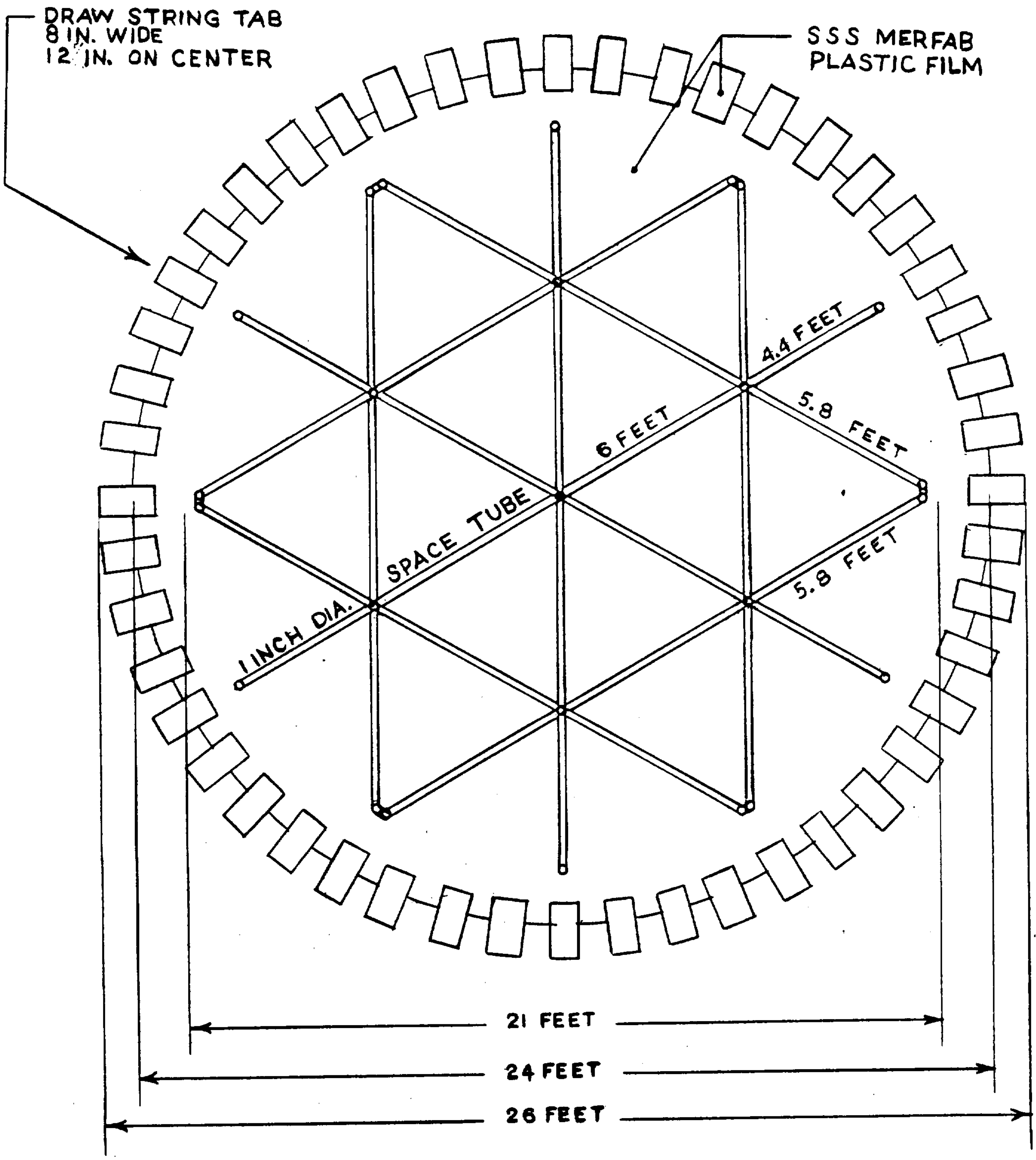


Fig. 31 The GSFC 22-ft. Torus and the way the SSS test segment is held to it.



SPACETUBE LAYOUT

Fig. 32 The Space Tube Configuration in the Test Segment Seen In Plan Before It Is Accommodated To The GSFC Torus F-32

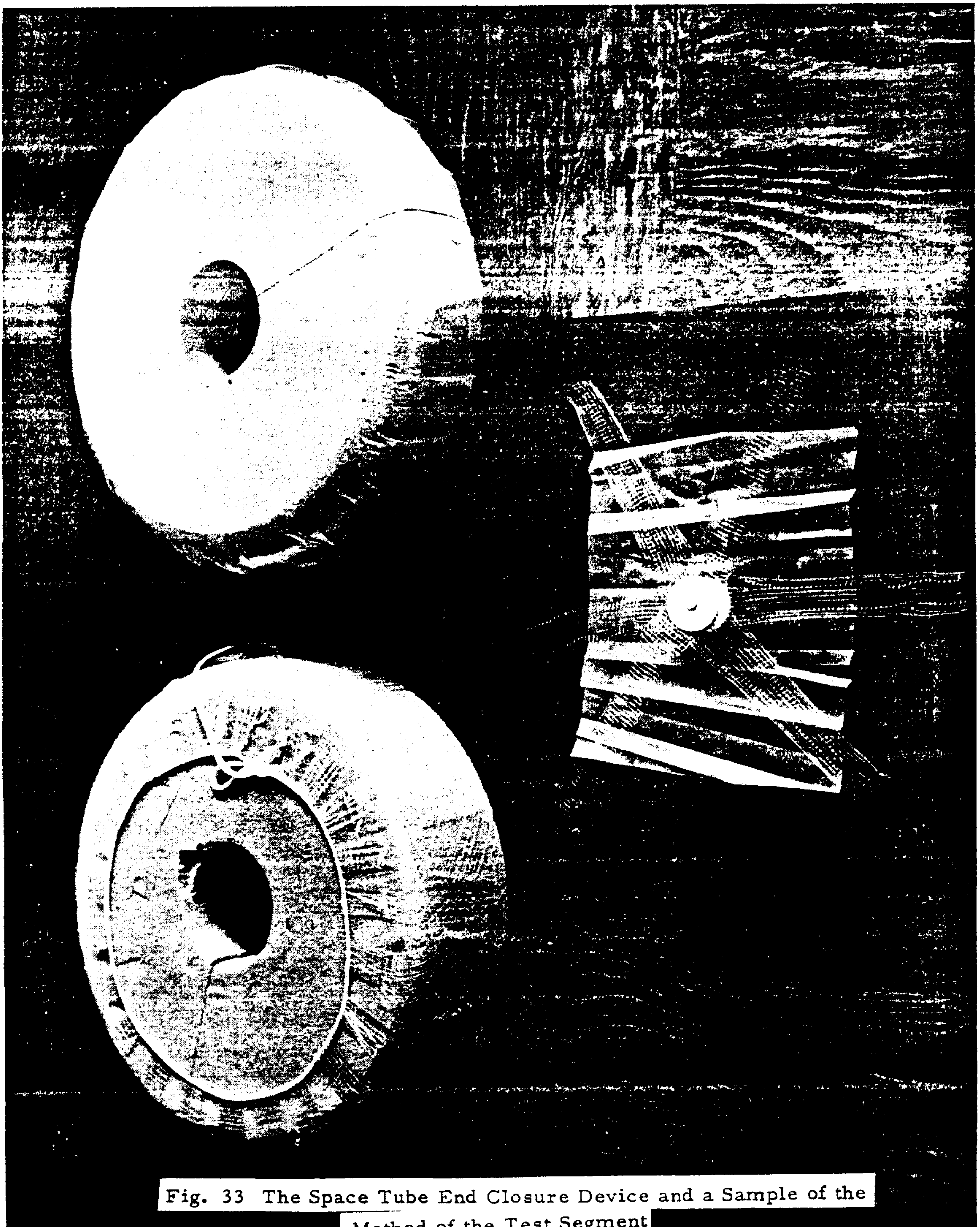


Fig. 33 The Space Tube End Closure Device and a Sample of the Method of the Test Segment

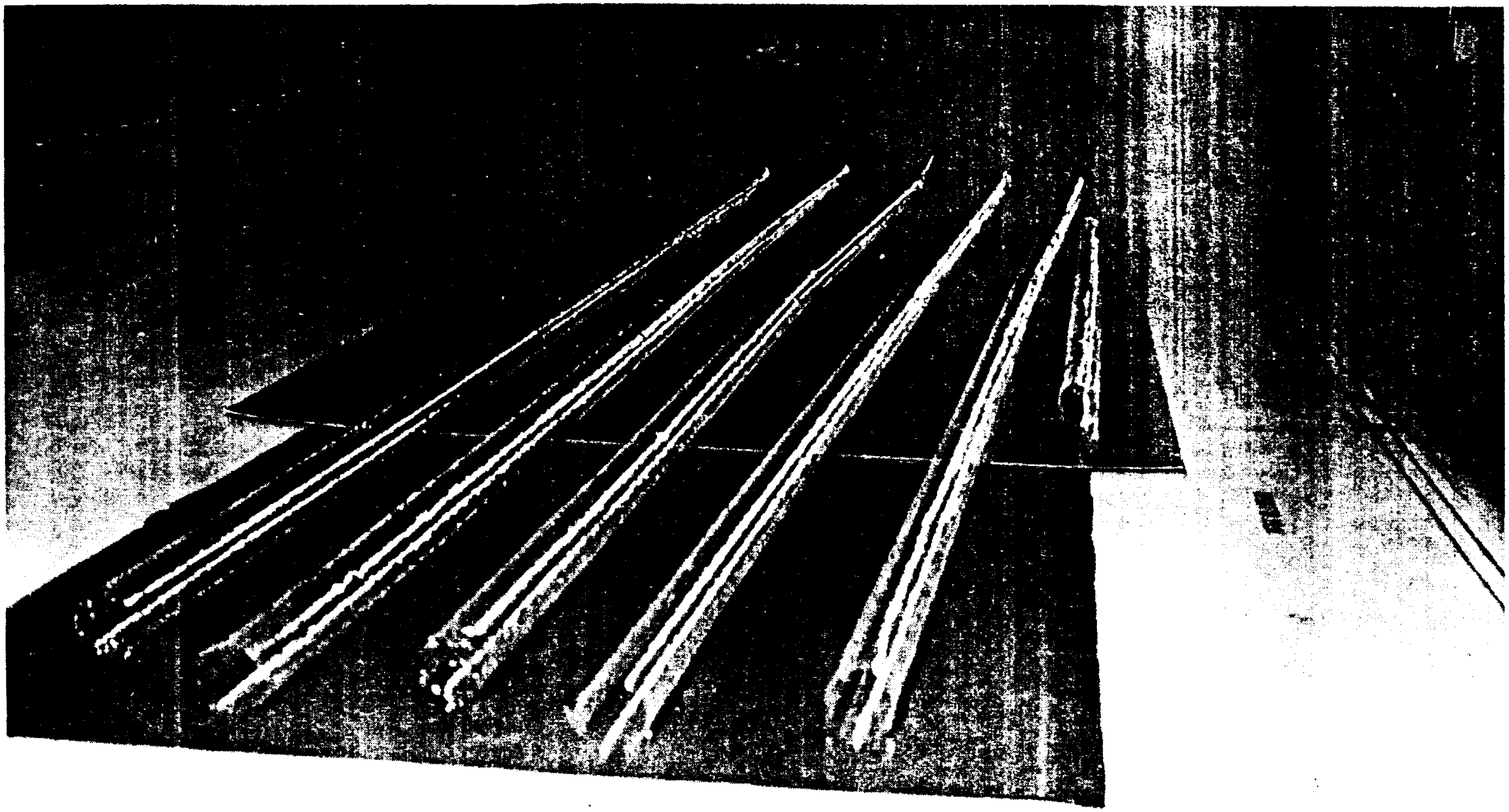


Fig. 34 Eight-foot specimens of Space Tubes made on the Winder-Welder. There are more than 7000 individual welds in the photograph, and the crossing of two wires is invariably welded.

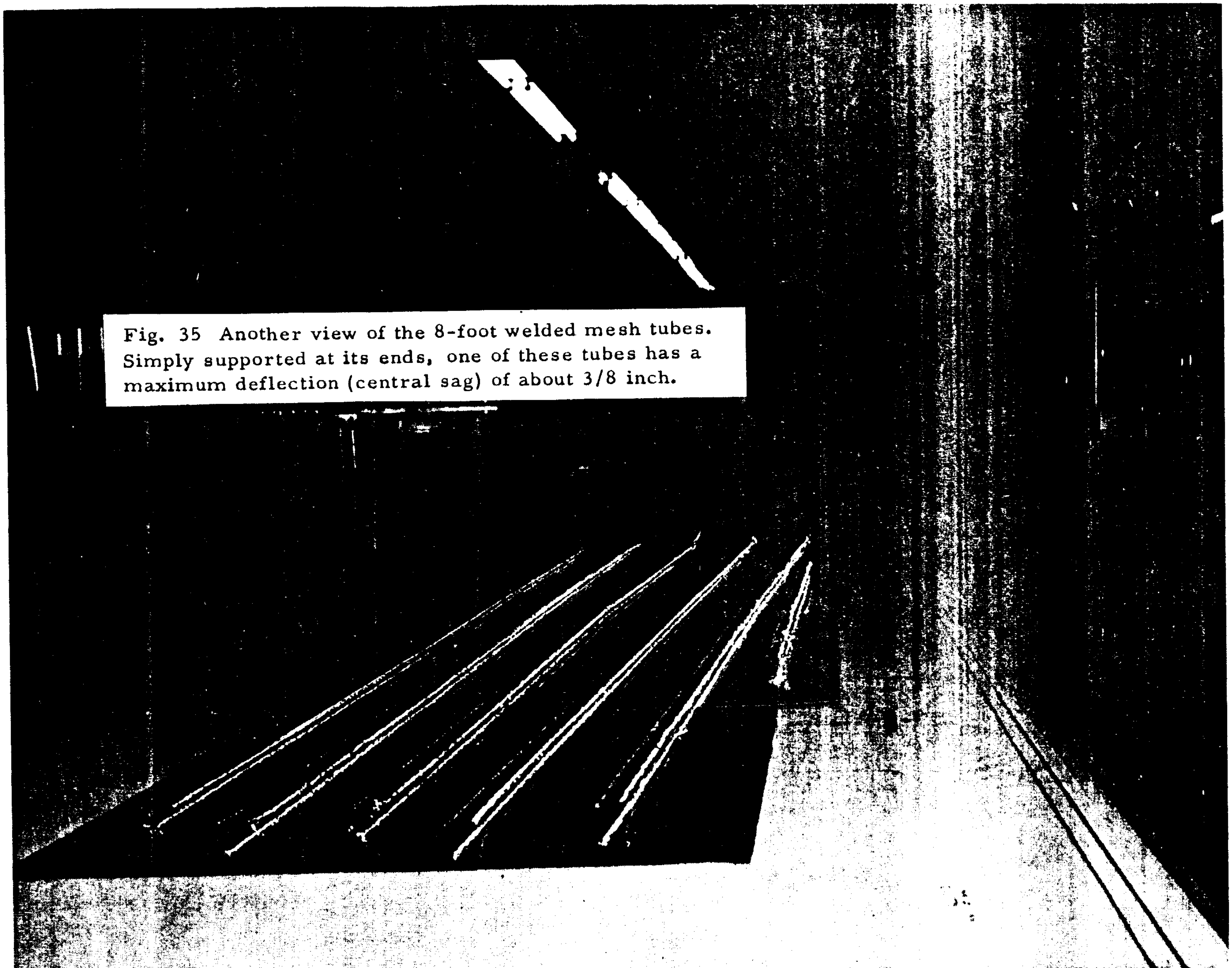
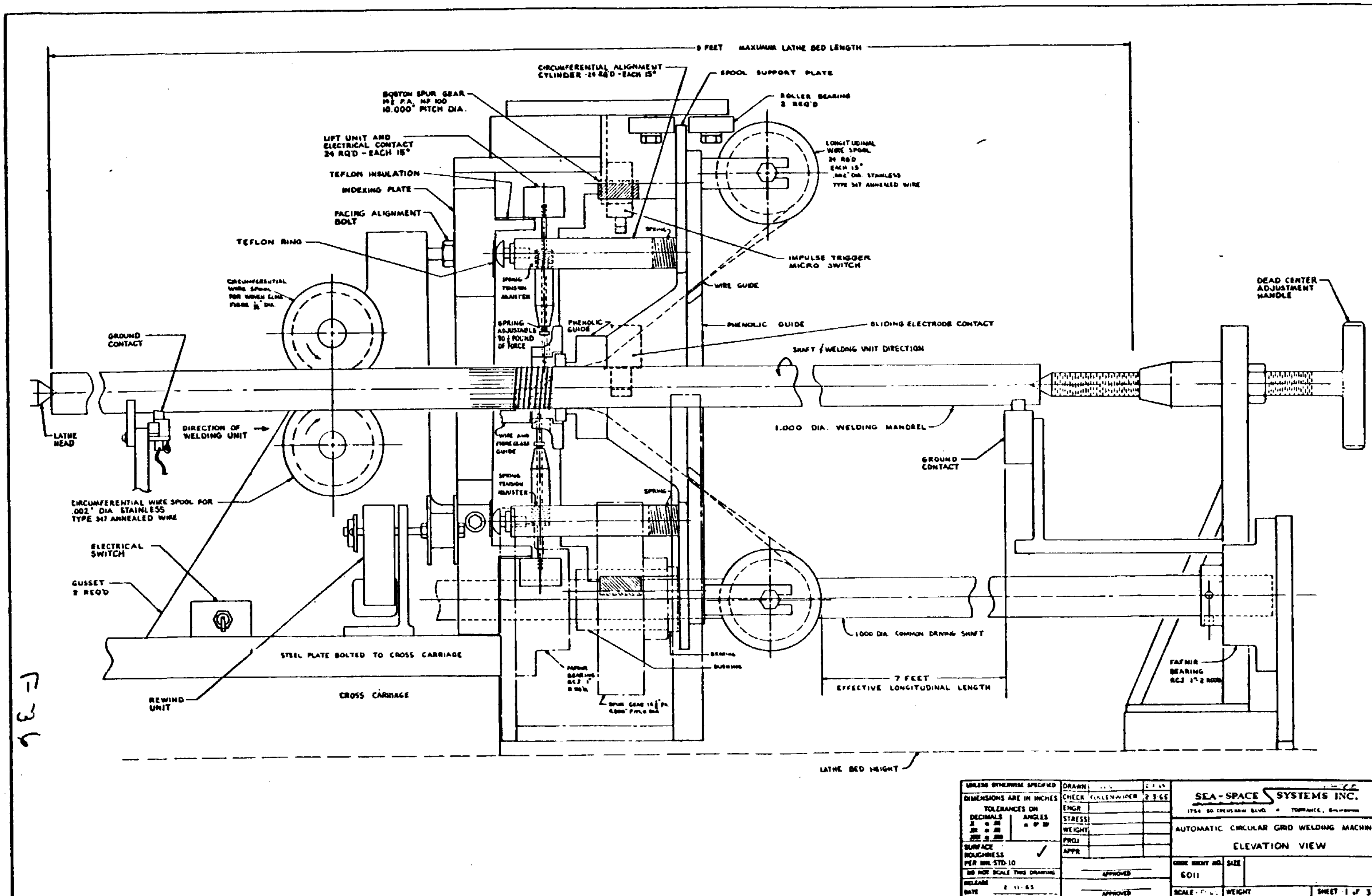


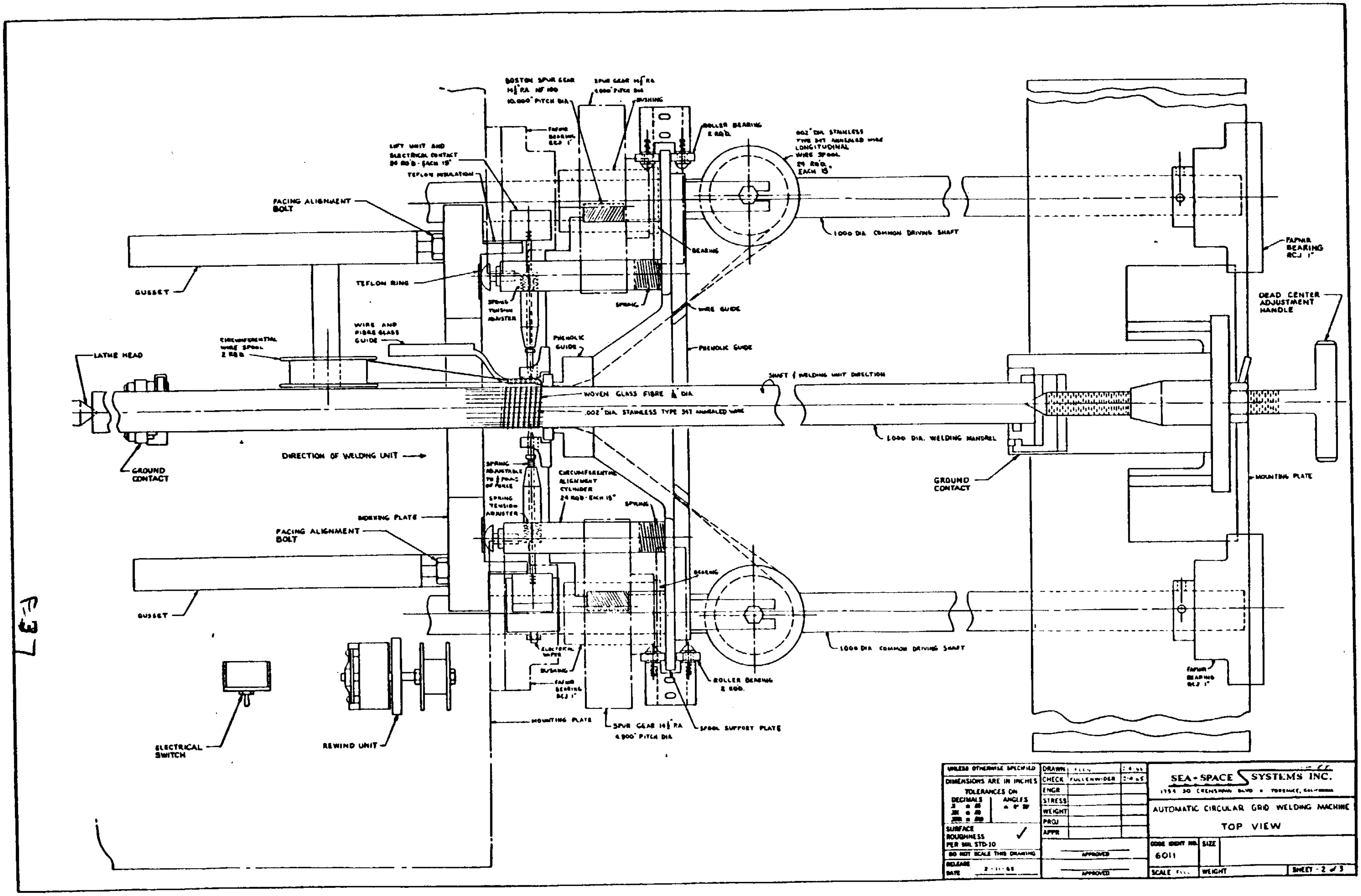
Fig. 35 Another view of the 8-foot welded mesh tubes. Simply supported at its ends, one of these tubes has a maximum deflection (central sag) of about 3/8 inch.

Figure 36



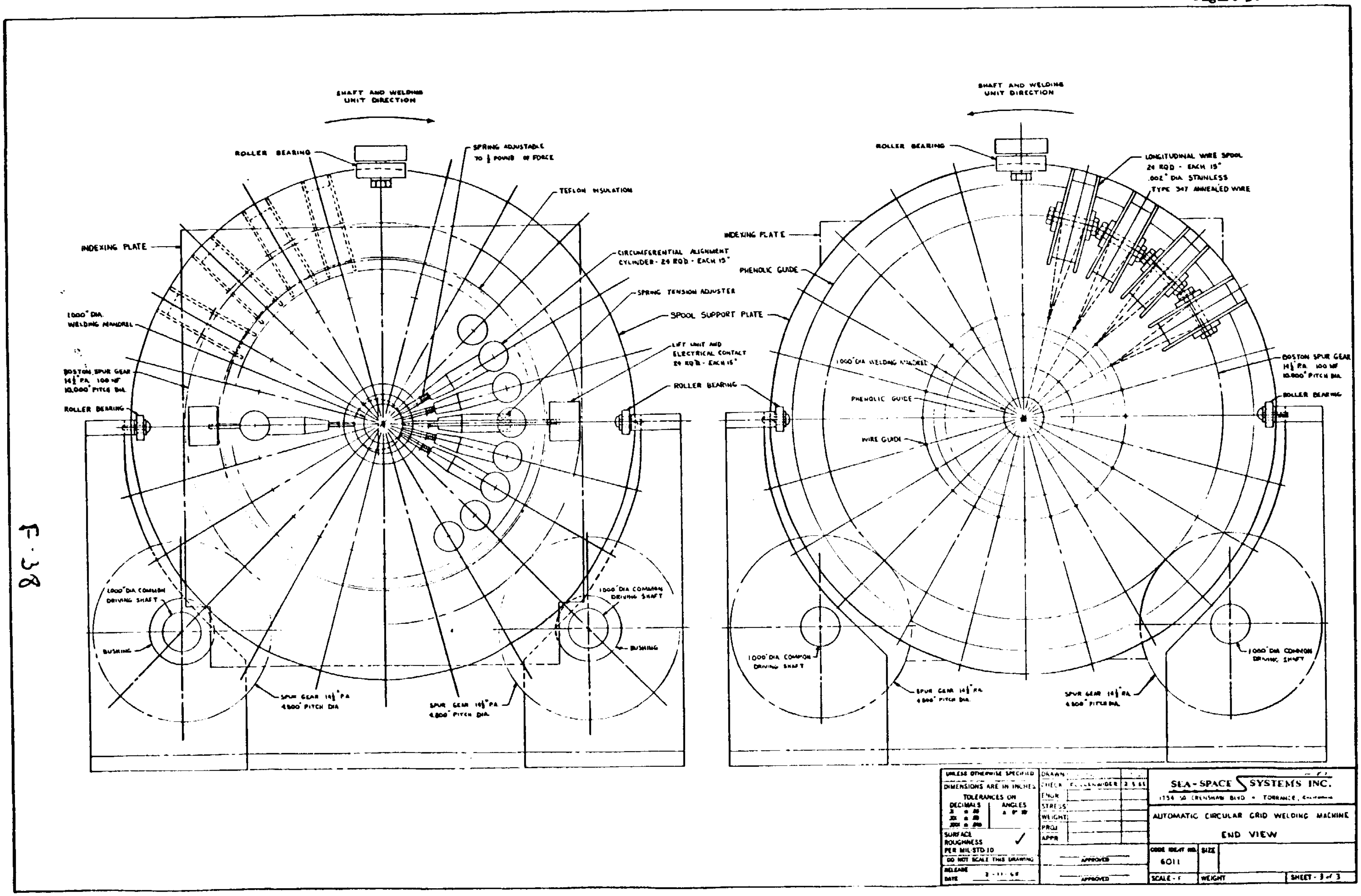
F 36

Figure 37



F-37

Figure 38



F-38